Enabling On-Demand Decentralized IoT Collectability Marketplace using Blockchain and Crowdsensing

Duc-Duy Nguyen
Insight Centre for Data Analytics,
Data Science Institute, National University of Ireland
Galway, Ireland
ducduy.nguyen@insight-centre.org

Muhammad Intizar Ali
Insight Centre for Data Analytics
Data Science Institute, National University of Ireland
Galway, Ireland
ali.intizar@insight-cetnre.org

***Abstract*—The Internet of Thing (IoT) is generating an unprecedented volume of data, facilitating the rise of the Data Economy. Under this ecosystem, the IoT data marketplace (IDM) provides an online platform for IoT data trading. Most current IDM solutions are centralized, serving as an intermediary between the data provider and consumer. They support selling and buying data collections (e.g. pre-collected data sets and data streams). However, as these data collections are historically collected without having any priory requirements and preferences given by the data consumer, it is very likely that most of these data collections cannot fulfill data consumer requirements. Redundancy, poor data quality, inaccuracy and limited financial incentives are common problems for existing IDMs, thereby making them financially ineffective. Due to the temporal nature of IoT data, the issue of pre-collection becomes even more critical as it is not trivial to re-collect data from the past.**

This paper presents a novel framework with a new on-demand market model, namely Decentralized IoT Collectability Data Marketplace (DCDM) model. Difference from the conventional IDM models where merely data collections are considered as a commodity, our model also involves operational factors such as data provider availability, operationality, contextual and geographical location etc. This empowers our framework to trade not only the dataset but rather an ability of the data provider to fulfill the collection task. Our game-changing approach is realized using a combination of Blockchain and Crowdsensing techniques. We first explore the concept of *”Data Collectability”* for IDM, then build a model to deploy our approach on IoT context. Furthermore, we identify potential applications and open research challenges.

***Keywords*-Internet of Things; IoT; Blockchain; Data Marketplace; Crowdsensing; Decentralized System; Smart Contracts**

I. Introduction

With the proliferation of numerous IoT and mobile devices, an enormous amount of data is being produced at a very rapid rate. With the estimation of over 20 billion devices connected by 2020, it is expected that a huge number of devices will continue to produce data streams containing sensor data observations. According to Forbes, the estimated market size of IoT is around 1.5 trillion USD by 2020[1]. However, a key open research challenge is to tap these data streams from IoT devices and build useful applications on top of IoT infrastructure. Most of the existing IoT applications are designed to address a domain specific problem, hence resulting in data silos. The true potential of IoT can be achieved by establishing open data platforms which can potentially host a large amount of data which can be re-used by multiple applications on demand.

With the growing popularity of IoT and sensing devices, a large number of data providers are normal citizens, producing various types of data streams regularly. The most common example of such data streams is a GPS trajectory generated by any smartphone user. Besides GPS, nowadays a smartphone contains 15 sensors on average. Additionally, IoT devices are an integral part of smart cars, smart homes and weather stations, etc. However, due to the privacy and security concerns and lack of monetizing mechanisms for common data streams, there is a very limited interest in users to share data produced by their personal devices. Beside security and privacy concerns, the technical challenges (both at hardware and software level) involved to publish IoT data are also a major hindrance in the wide spread of IoT. Web of things enables publications of IoT data on the Web is such a way that normal users with limited technical knowledge can easily publish their data on the Web [1]–[3].

Realizing the true potential and value of data produced by users, the concept of building a marketplace is gaining momentum. These marketplaces provide a common platform for data producers to sell their data which can be purchased by data consumers depending on their need. Typical information flow for such marketplaces is that the data producer or owner upload their data including its features similar to any online store. While data consumers can browse through samples and make an online purchase of data based on their needs. However, the nature of IoT data is such that it is not so trivial to build common data marketplaces for decentralized IoT infrastructure which can handle the amount of streaming data. However, the concepts of collect-ability, on-demand data collection decentralized IoT data markets are so far almost non-existent.

In this paper, we propose an on-demand decentralized

[1]https://tinyurl.com/y6qleg5p

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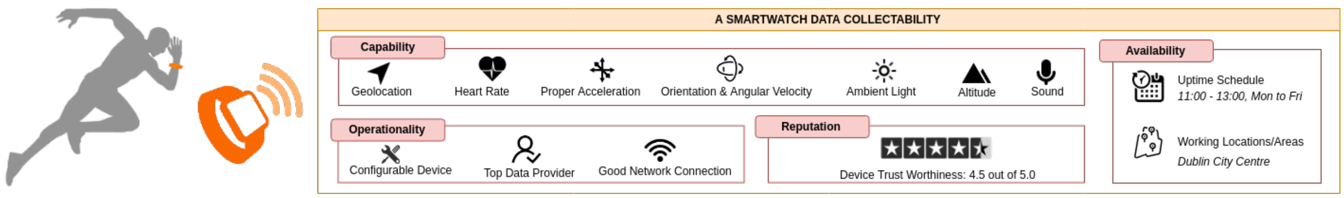

Figure 1. Example of the collectability of a smartwatch with multiple built-in sensors.

solution for IoT marketplaces using the concept of collectability. It employs crowdsensing capabilities in order to build a new business model for trading IoT data in the marketplace. Using our framework, users can launch requests for crowdsensing and data providers can collect data on-demand following the requests from data consumers. We leverage the Blockchain networks to build a decentralized marketplace for IoT.

II. Related works

Although IoT Data marketplace, Blockchain and crowdsensing are well-investigated disciplines, very few cross-domain studies has been conducted. Several industrial solutions are proposed for selling IoT data in a centralized manner, such as Dawex (www.dawex.com), Quandl (www.quandl.com) and Xignite (www.xignite.com). From scientific perspective, many studies introduced centralized cloud-based systems, such as Sensing-as-a-Service model [4] to enable an open IDM. However, their centralized architecture raises many privacy and resilience questions. In recent years, there has been a growing interest in decentralizing the market with Blockchain technology or decentralized repositories [5]. Smart contracts are implemented to enhance transaction integrity, reputation mechanism and privacy preservation [6]. A few Blockchain-based decentralized data stream markets have emerged recently, such as Wibson (www.wibson.org), Streamr (www.streamr.com). Preliminary works focused on using Blockchain, such as Ethereum (www.ethereum.org), Bitcoin (www.bitcoin.org), Ripple (www.ripple.com/xrp/), especially smart contract for handling transactions and financial reward delivery resulting in a decentralized payment service. Nevertheless, the data doesn't travel directly from provider to consumer, thus a complete decentralization is not fully realized. This challenge is addressed by Jiang et al. [7] with a Peer-to-Peer Crowdsensing Data Sharing model. They investigated the marketplace from the game-theoretic perspective, focusing on proposing an effective gamification strategy. Zheng et al. [8] emphasized on the profit perspective of the market and proposed VENUS, a framework of profit-driven data acquisition, aiming to maximize the profit and minimize the payment. However, to the best of our knowledge, the existing solutions are inadequate to bridge the gap between the three aforementioned fields.

III. Data Collectability Marketplace

The IoT facilitates an immediate access to the sensed data using a network of identifiable devices interconnected via the internet [9]. These devices are equipped with sensors that can detect events or changes in the environment. Existing IDM solutions are centralized and buy/sell historical data collections. We consider an alternative approach to migrate from the dataset-based approach (data collections) to the service-based approach (data collectability).

A. Data Collectability of IoT devices

Data collectability refers to the capability of an IoT device or sensor to collect and transmit sensory data to the designated destination. As todays' sensors are ubiquitous (e.g. smart building, smart factory and smart cities) and often constantly on the move (e.g. smart cars), the concept of collectability must also consider operational factors, such as human factor (i.e. device owner/operator availability) and communication infrastructure.

Collectability can be assessed from the following four major dimensions:

- *Capability* refers to the hardware-related characteristic of a device. It also indicates the type of data and technical specifications of the device and collected data.
- *Availability* depicts the uptime of the device, as well as its geographical and temporal availability range.
- *Operationality* indicates whether a device can be correctly calibrated and configured to meet a sensing task. The human factor is the major determinant of both the quantity and quality of the collected data e.g. network administrator or device owner's ability to operate and troubleshoot the device.
- *Reputation* related to the historical performance of sensors and their owner/operator. It is mainly relying on automatic feedback and user reviews, showing how well the device carried out sensing tasks in the past.

Figure 1 exemplifies the data collectability of a smart watch with 7 different sensing capabilities, 3 operational configurations, a reputation score and a time schedule for availability. This scenario shows how normal sensing devices can offer a service of collectability.

B. Collectability Productization and Monetization

IoT data collectability could be considered as a service or commodity, where device owners can trade the right

Table I
A COMPARISON BETWEEN COLLECTION-BASED AND COLLECTABILITY-BASED DATA MARKETPLACE

		Data Marketplace Model Approach	
		Collectability-based	*Collection-based*
On-demand data collecting	***Pre-ordering***	✓	✗
	Dataset customization	✓	✗
Nature of Data	***Scope***	Future	Historical
	Type	Stream	Static/Stream
Quality Assessment	***Collecting process***	✓	✗
	Provider reputation	✓	✓
	Device reputation	✓	✗
	Finished dataset	✗	✓
Privacy and Ownership	***Device ownership***	Provider	Provider
	Data ownership	Consumer (transferable)	Provider (transferable)
	Right to use the device	Consumer	Provider

to use their sensing force for a specified time period in exchange for a monetary reward. For example, the owner of a smart watch (as shown in Figure 1) can offer the collectability of gyroscope and accelerometer sensors to a researcher who wants to collect real-time data for training activity recognition models.

However, due to the dynamic nature of IoT data and multiple influential factors, it is not easy to productize and monetize the data collectability without sophisticated solutions. A decentralized marketplaces environment, combining conventional marketplace principles with community monetization mechanisms (e.g. gamification), distributed ledger technology (e.g. Blockchain) and crowdsensing technique is one of the most prominent approaches.

C. *Data* collectability *versus* collection *marketplace*

Compared to data collection marketplace, data collectability marketplace has many distinct advantages as shown in Table I. Although both approaches have similar goals, the collectability approach focuses on on-demand real-time data, providing an opportunity to produce customized datasets in a cost-effective way. The most important feature is the support for on-demand data collecting of future data streams ensuring high quality and production rate. Data collectability also clearly distinguishes the device's ownership and right-to-use providing methods for the device and including confidentiality and copyrights.

D. *Selling in a reserved sensing session*

Collectability marketplaces bring an added value by allowing the provision of data collectability as service during exclusively reserved sessions. This will allow data brokers to reserve collecting session from providers, then trade or share it with a third party (i.e. consumer). The open market can itself adjust to the price according to supply and demand, guaranteeing a free trade environment. The marketplace can also impose regulations to ensure fair, open and trustworthy trade between data providers, consumers and other stackholders.

IV. IoT COLLECTABILITY MARKETPLACE MODEL

In this section, we define a model for IoT Collectability Marketplace and identify major actors involved, including the interactions between them. We also lay down major functionalities of our proposed marketplace.

A. *Marketplace Actors*

We identify the following four major actors in the IoT Collectability Marketplace;

- **Producer**: A working sensor that can collect sensory data and transmit to a defined destination.
- **Provider**: An intermediary device (autonomous, or partly operated by a human) with sufficient computing power and network connection in order to collect sensory data from producers. Providers also manage all connected producers and serve as an intermediary node in the network e.g. gateways.
- **Consumer**: A machine or human capable of receiving purchased data while having a purchasing power to complete the transactions.
- **Trader** or **Broker**: A trader or broker is an intermediary facilitating transactions between the data provider and consumer, and in some cases, holding the stocks for future sale with a good price.
- **Marketplace Operator**: A combination of technologies and algorithms autonomously operating (controlled by a human) to facilitate smooth execution of data transactions at the marketplace.

B. *Marketplace Model*

As depicted in Figure 2, the DCDM Model consists of the following four conceptual layers:

Sensor and Sensor Owner/Operator layer consists of IoT devices with sensors as well as their owner or operator. This layer is operated by *producers*, who own collectability (as discussed in section III-A) with the intention to join the market. Producers can be stand-alone devices (e.g. camera), installed in another device (e.g. smartwatch, smartphone, and/or tablet), artifacts (e.g. car, ship) or structure (e.g. building, road system). Every sensor has a legal owner at a given time, who is not necessarily the same as the sensor operator.

Sensing provider layer consists of devices that can discover, manage and collect data from sensors. Their primary responsibility is to publish the collectability of sensors to a marketplace. This layer is maintained by providers who send data stream to the subscribed consumer. Traders and Brokers only perform buying and stocking activities without shuttling any data. It is mandatory that all providers are registered at the marketplace and their connected sensors' collectability can be automatically updated to the marketplace catalog.

Blockchain Network and Collectability Marketplace layer performs transactions, quality assurance and trading activities. Collectability marketplace provides a meeting

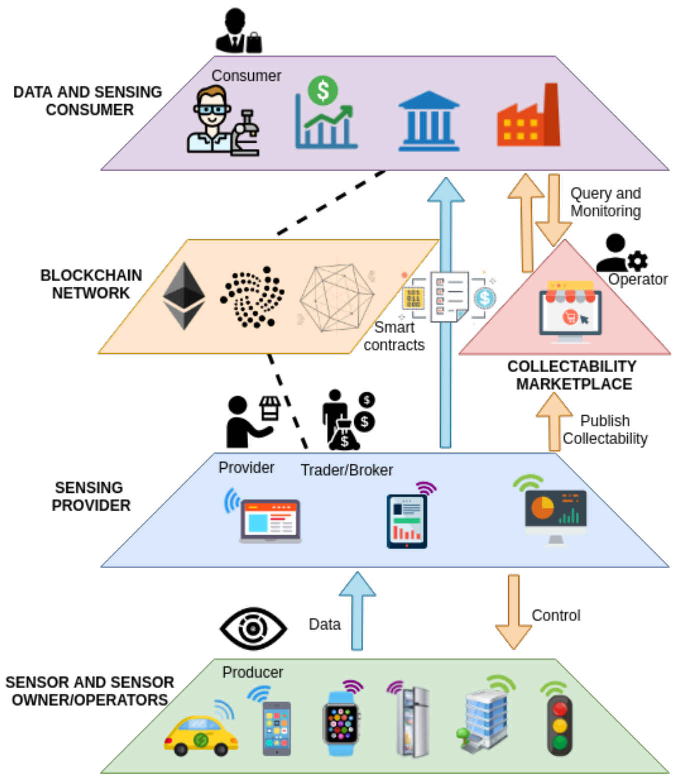

Figure 2. IoT Collectability Marketplace Model

place for all actors. Every exchange and transaction between stakeholders are legalized with smart contracts and deployed over a Blockchain network. This layer also monitors service quality level, enabling a reputation system for data providers. The Blockchain network is operated by its participants, whereas the marketplace is managed by the market operators.

Data and Sensing Consumer layer consist of human, applications and/or machines looking for IoT data. Every data consumer must register at the marketplace, proof their identity and purchasing power before making any transactions. Whenever a consumer places a request for data, the match-making method identifies relevant data sources and corresponding providers. If both the provider and consumer agree to a transaction, the marketplace issues and executes a smart contract between them. Once the contract is in place, the provider can send data directly to the consumer under the marketplace (optional) supervision.

It is worth mentioning that although the above list depicts a layered architecture, the actual topology of our model comes as a decentralized network, in which the Blockchain network serves as a backbone for all data and monetary transactions.

C. *Collectability Marketplace functionalities*

The primary functionalities of the marketplace are hosted at a decentralized collectability marketplace node, which integrates Blockchain and Crowdsensing components. This marketplace facilitates the recognition and negotiation between pseudo-anonymized or fully-anonymized actors. Data provision and integration carried out by providers and consumers themselves.

The functionalities of the marketplace include:

Institution: DCDM node sets up the roles and protocols for the interactions among actors. It maintains a catalog of collectability of all registered nodes as registered by providers and traders. It can also track the ability of consumer nodes to integrate data from multiple providers. Historical performance of both provider and consumer builds a reputation system, indicating their trustworthiness.

Recommendation & Pricing Mechanism: After receiving the query from a consumer via the DCDM portal, the marketplace searches for the best sources according to the collectability of registered nodes and recommends them to the consumer. After this, the negotiation between stakeholders starts to agree on the terms and conditions.

Contract & Transactions Once both providers and consumers reach an agreement, the marketplace creates a smart contract between them. The marketplace allocates a sensing task to stakeholders according to the agreement and monitors the whole process. All transactions are carried out transparently over the Blockchain network.

Quality Assurance This is one of the key services of the marketplace. Both consumers and providers are required to continuously send a statistical summary of the data stream to the marketplace for quality assessment. The outcomes of these tests serve as one input of the smart contract, and more importantly, contribute to the reputation score of participants.

V. COLLECTABILITY MARKETPLACE IN ACTION

In this section, we illustrate a use case of monitoring noise pollution level through crowd-sensing using our proposed marketplace.

Environmental monitoring. Urban noise is a serious environmental problem in today's cities, threatening the life of human and wildlife [10]. Thus, monitoring noise pollution, especially anthropogenic noise from construction activities is critical to protect public health. A city council wants to monitor the hazardous noise levels of a large construction for a period of 2 months. However, for such a short period, purchasing a new sensor network and communication infrastructure is not financially viable. Therefore, as a consumer, the council looks for a data collecting solutions on DCDM. Figure 3 exemplifies the efficiency and effectiveness of DCDM when supporting community-based noise data collection. The process commences when the consumer node operated by city council's staff submits a query to the DCDM web portal (violet rectangle), indicating requested data type, technical specifications, preferred temporal and spatial limitations. The DCDM portal

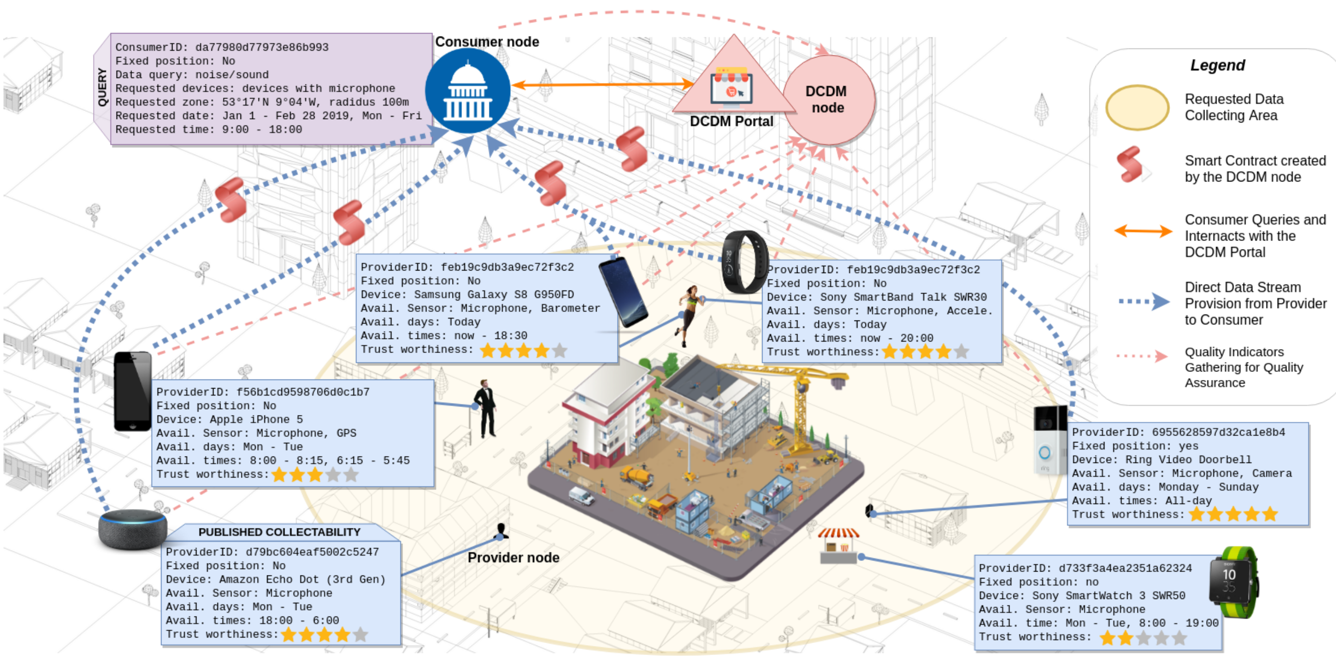

Figure 3. Noise pollution data collecting with the support of DCDM

passes the query to DCDM node to find the best providers according to the collectability information published (blue rectangle). Because, in this case the data producers are available at different timings, service composition function of DCDM manages to recommend the best combinations for collectability. Then, the terms and conditions including prices are negotiated, and once the agreement is reached, the DCDM node creates a smart contract for each provider (red scripts) which is signed by all parties including DCDM. At an agreed time, the provider starts sending data directly to the consumer. Meanwhile, quality indicators are collected by the DCDM node to evaluate the quality of service and quality of information, as well as the behavior of both sides. Upon the completion of data collecting process, the financial reward are automatically distributed as defined on the smart contract. The above example is just an illustration of potential use case. However, we strongly believe that DCDM has strong potential in various domains such as Smart Mobility, Smart Cities, Smart Health-care and crowdsensing based data collection scenarios.

VI. Advantages and Open Research Challenges

A. Advantages

IoT Collectability Marketplace Model proposes a new approach for IoT data marketplace. The major advantages of our model include:

Decentralized architecture: The model is built on top of Blockchain decentralized network. The DCDM node solely acts as a broker and optionally as a quality controller. In particular, the most important tasks (i.e. data transmission and transactions) are carried out in a peer-to-peer fashion between data providers and consumers. Therefore, participants do not have to rely on any central authority and avoid a central point of failure. This makes our market model relatively resilient compared to the centralized solutions.

Community-based: Our model takes advantage of the unused pervasive IoT devices to sense and collect data, thus generating a remarkable sensing force. The collectability approach enhances this force with flexibility for the data provider and cost-effectiveness for the data consumer. It empowers users to take control over their information and transactions. Furthermore, the consensus protocols (inherited from blockchain network) bring the policing role (which were previously held by a third party) to the community, promoting transparency and trustworthiness of the network.

Boosting performance with reward mechanism: Choosing a trusted data provider is a critical challenge for both data marketplace and crowdsensing system. Our reputation system is built using the historical transactions in a shared ledger, which is tamper-proof and immutable. Such system ensures a transparent, traceable and trusted execution of transactions for both data providers and consumers.

Private and secured: Our model inherits data anonymization methods, which are the well-developed feature of both Blockchain and crowdsensing realms, which further strengthens the security and privacy of all participants of our marketplace.

A sharing economy: Collectability is not the data itself, thus it can be employed by multiple consumers. By enabling the Collectability Sharing Economy, our model allows companies and individuals to share collected data with partners or other third parties after consent from the provider and giving an appropriate reward. It benefits data consumer with inexpensive data collecting while giving the provider the chance to maximize their income.

Industrial implications: Our model extends the last stage in the evolution of industrial sensing by combining human wisdom with the sensing network [11]. Potential applications include business intelligence, marketing, personal, product and environmental monitoring.

B. Open Research Challenges

Bringing together collectability marketplace and IoT crowd-sensing provides many research and business opportunities. A few potential research directions include:

Marketplace Institution: Sensing devices are operated by anonymous members of the community, making it difficult to fairly shape behaviors of stakeholders. Thus, solid protocols are needed, including transparent trust management and quality assurance mechanisms.

Authentication and Verification: Governing a large number of IoT devices with limited resources and a high mobility is a complex problem. More importantly, collectability information provided by providers need to be automatically and independently verified to prevent fraud and speculation.

Incentive: Feedback/reward is crucial to encourage good behaviors between participants, hence enforcing the institution. Thus, further investigation to build an integrated incentive mechanism is required, combining both financial as well as reputation based rewards.

Scalability: As the foundation of this model is Blockchain network, scalability becomes one of the most problematic concern [12]. Realizing the potential bottleneck for our marketplace, we kept the transmission of actual data away from the network of transactions and intentional avoid storing large IoT data streams at the transaction ledger. However, it is important to have a scalable solution which can handle a large number of IoT data streams with high volume and velocity.

Privacy and Security: Many types of data, such as medical records or payment data are sensitive for each individual. Therefore, more studies is critical to protect participant's privacy and security.

VII. Conclusion

This paper presented a comprehensive overview of IoT Collectability marketplace model and how it fits IoT data acquisition. We elaborated a new market approach using our model, which focuses on trading collectability of IoT devices following a peer-to-peer model. We provided an overview of functionalities and interaction between actors on the market. We discussed how our model can empower community-based sensing with remarkable implications in various domains in the modern economy, such as environmental monitoring, smart mobility, smart healthcare. We believe that our work is one of the pioneering approaches to combine blockchain and crowdsensing technologies and facilitating on-demand decentralized marketplaces for IoT data collectability.

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