Trading of Cloud of Things Resources

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***Abstract*— Cloud Computing and Internet of Things (IoT) continue to emerge as revolutionary paradigms to support wide range of real world scenarios. They promise benefits for increasing number of applications, including health, smart cities, smart homes, smart logistics, video surveillance, energy and environmental monitoring. Independent deployments of each technology have issues that can be resolved partially or fully by integrating Cloud and IoT. This integration forms a new paradigm that is called Cloud of Things (CoT)supporting Everything as a Service (XaaS) service model. Despite the issues integration resolves, the integrated services will suffer from issues that Cloud and IoT offerings previously encountered. This includes interoperability, ambiguous SLAs, QoS, elasticity and reliability concerns. This paper argues that commoditising CoT resources will help resolving these issues. This paper aims to; 1) review the state-of-the-art in CoT literature 2) propose a conceptual model for CoT marketplace and its basic trading processes.**

I. INTRODUCTION

Cloud Computing and Internet of Things have evolved and grown independently from each other. Cloud Computing is a model of offering computing capabilities as metered services rather than physical products. This offering is characterised to be provisioned on-demand elastically, ubiquitously accessed and pooled as a part of shared resources [1]. Cloud Computing is delivered under one of the following traditional service models; 1) Software as a Service (SaaS), 2) Platform as a Service (PaaS) and 3) Infrastructure as a Service (IaaS). Beside the service model, Cloud Computing is deployed under one of the following types: 1) Public Cloud, 2) Private Cloud, 3) Community Cloud, 4) Hybrid Cloud and 5) Virtual Private Cloud.

Along with its technical value, Cloud Computing has its own significant economic impact. Cloud resources are usually provisioned on-demand automatically or with minimal human intervention. This reduces the cost of resources management, enables pay-per-use only and reduces upfront investment on new computing infrastructure [2]. These economic and technical features attracted large deployments globally that become the current trend for many businesses. Gartner estimates the value of global public cloud market to reach $204 Billion by 2017 and expect continuous growth afterwards [3].

Internet of Things (IoT) is a recent and less mature technology than Cloud Computing. IoT is described as worldwide interconnected and interactive objects (things) that can be identified, monitored and controlled over the internet [2], [4]. The IoT is heavily dependent on the development of sensor networks. Sensor Networks are composed of tiny computers known as “motes” with embedded CPUs, low-cost sensors and low-power radios [5]. These motes form (often wireless) networks that are capable of sensing the physical world. Sensor networks collect data from sensors, collate, aggregate and transfer this in forms of data streams to back-end computers for processing. Those streams of data are used to support IoT applications such as home automation, industrial control and environmental monitoring. The deployment of IoT has rapidly increased in the last few years. McKinsey estimates the potential economic impact of IoT to be between $4-11 trillion by 2025 [6]. Gartner predicts that IoT will need five to ten years for mainstream deployments with over 20 billion connected things in 2020 increasing from 6.4 billion in 2016 [7].

Despite the recent advances of Cloud Computing and IoT in terms of their computing capabilities, both technologies have been pushed to their limits by new real world scenarios. This raises new challenges and new applications are unlikely to be supported by separate deployments of either Cloud or IoT. Even though Cloud is a much mature technology than IoT, it still needs a companion to extend its coverage to support more distributed and flexible real world applications that are far away from Cloud data centres [8]. IoT also needs a Cloud with virtually unlimited communication, processing and storage capabilities to handle the volume and variety of its generated data. IoT should benefit from the scalability and reliability of Cloud Computing to support its heterogeneous things. As a result, Cloud of Things has emerged as new paradigm to merge both Cloud and IoT and to deliver wide range of new services under Everything as a Service (XaaS) [9].

As Internet of Things (IoT) deployments increase, it is likely that IoT resources will increasingly become commoditised. Currently, to create an IoT application, hardware and software have to deployed. In a CoT marketplace, resources are considered commodities and not physical assets. IoT things will be available to be leased under pay-per-use model and used with any applications. The emergence of CoT, which provides a consistent pricing and access model for accessing infinite global IoT resources, has further accelerated this phenomenon. There is a growing commoditisation of IoT, particularly in the areas of Cloud Computing [10], leading to the increased deployment of CoT integrated services. Cloud Computing also offers its cost model to enable end-to-end service provisioning where applications can be accessed on demand from anywhere [11]. The commoditisation of

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CoT should result in overall decreased prices, an increase in the numbers of services, and improved performance of services as a whole [12].

The current market of Cloud Computing is orchestrated and dominated by giant vendors including Amazon, Google, IBM, Salesforce and others. In contrast, IoT market introduces larger number of SMEs and start-ups of IoT software, hardware, platforms and system integrators. IoT has also attracted the attention of dominant vendors of Cloud market including Google and Amazon that have already started integrating Cloud and IoT [13], [14]. Both market offerings still lack several functions and features that will be transferred to CoT market if they are not resolved. This includes interoperability, fair SLAs, transparent pricing policies and achievable QoS.

For the commoditisation of CoT resources to work efficiently, access to these resources needs to be global, purchasable and efficient. One approach to achieving this goal is the creation of a non-vendor marketplace to trade these resources. This paper proposes an architecture for trading commodity CoT resources based on multi-attribute combinatorial exchange. It demonstrates how this approach can support generic CoT applications.

This study is structured as follows. Section 2 is a brief review of Cloud and IoT integration and their resources trading. Section 3 discusses the motivations for CoT market. Conceptual model of the marketplace and its vocabulary are presented in Section 4. Section 5 concludes the study.

II. Cloud of Things (CoT)

Cloud Computing and IoT evolved independently. Both technologies are attractive and rich as research domains. The literature has increasing attention on the integration of Cloud and IoT where each of the two technologies is considered as complementary to the other. Despite the amount of attention it receives from academia and industry, there is no standard name for the integrated paradigm. Common names found in literature include; CoT, Internet of Things Cloud (IoT Cloud), Cloud of Things, Cloud of Everything and web of things (WoT). CoT will be used throughout this study. Furthermore, there is no standard definition or description of CoT. We refer CoT to the integration of Cloud and IoT to form a new distributed paradigm of connected IoT technologies to Clouds via the internet to provide new services under (XaaS) model [15]. This section highlights related works on motivations of CoT integration, common integration approaches and the existing gap of trading CoT resources.

A. Motivations for CoT (Heading 2)

Considerable literature has motivated the integration of Cloud and IoT to fill the gaps of each technology. Motivations fall under three categories; 1) functional properties, 2) computing resources and 3) business values.

1) Functional properties: Significant part of reviewed literature focus on limitations and several missing properties that hinder the deployments of IoT. Limitations are inevitable due to the high heterogeneity of IoT in terms of devices, software and communication protocols deployed. This results in lacking interoperability, scalability, flexibility, reliability and availability. Security is also challenged to great extent [4]. IoT would greatly benefit from the integration with the Cloud. The aforementioned properties are considered integral part of any recent Cloud offerings [16]. These properties should enhance the functions of IoT improving its trustworthiness and business value to attract new deployments and users.

2) Computing resources: The most recent literature is extensively focused on one or more of limited IoT capabilities. This includes limited energy resources, basic computation capabilities, limited or no storage available and limited communication capacity.

- **Computation:**IoT devices usually have minimal processing resources due to the power constraints. They collect data and transfer it to more powerful back-end nodes for extensive processing and analysis. These limitations cause two issues for IoT; 1) real-time analysis and responding to some critical scenarios are not possible, 2)scalability with poor processing resources is very challenging. This may answer why IoT has less deployments in emergency, security and military scenarios. Cloud can lift the par of IoT by acting as its back-end aggregator and processor. Thus enable scalability and real-time processing for more complex real world implementation [4]
- **Storage:** Data produced by IoT devices is characterised by its size (volume), types (variety) and generation frequency (velocity) [17]. IoT by nature is big data producer but with very limited or no storage capacities. This motivates the integration with the Cloud. Cloud offerings are virtually unlimited, on-demand, cost effective and scalable storage capacities to accommodate IoT storage requirements [18]. This would result in new technical and business opportunities as well including ubiquitous access to data, Cloud-level security [19] and the ability to share data with third parties [20]

3) Business values:: along with the technical aspects that motivate integrating Cloud with IoT, business benefits attract more industrial attention than academia. The current business model of Cloud Computing reduces the costs of investments on IT infrastructure and the operational costs. Furthermore, the business risks of managing IT resources are shifted to Cloud providers [4].

B. Integration approaches

The integration of Cloud and IoT can be achieved by different approaches. Yet, there is no standard or commonly agreed approaches that can be found in the literature but started to be addressed and identified in several recent works. [2] surveyed wide range of related work and identified three main approaches for integrating Cloud and IoT, namely 1) minimal integration, 2) partial integration and 3) full integration.

- **Minimal integration:** In this approach, Cloud has no real changes to its service or deployment models. IoT platform or middleware is deployed into Infrastructure as a Service or Platform as a Service Cloud to utilise the Cloud services [21]. Examples of Cloud services utilised by IoT using this approach include virtualisation, data processing, data analysis and Cloud storage[2]. Existing solutions that demonstrate this approach are proposed by [22] and [11].
- **Partial integration:** Changes to the deployment of both Cloud and IoT is performed to some extent in this approach to achieve higher level of integration compared to minimal approach. The IoT middleware or platform is deployed into the Cloud to provided a new service models based on the abstractions of IoT things [21]. Examples for new service models resulted from this integration approach are Sensing as a Service (SaaS)[23] [24], Sensing and Actuation as a Service (SAaaS) [25] [26] and Smart Object as a Service (SOaaS) [27].
- **Full integration:** This approach aims to achieve the highest level of integration between Cloud and IoT by extending the traditional Cloud service models (SaaS, PaaS,IaaS) to include functionalities of IoT things. This would provide IoT services as integral part of Cloud services[21]. Proposed solutions based in this approach are City Infrastructure as a Service (CIaaS), City Software as a Service (CSaaS) and City Platform as a Service (CPaaS) [28].

III. Motivations for CoT Marketplace

[4] The rapid growth of the IoT has led to a large number of providers of hardware and software platforms. The costs of building and deploying IoT applications is dropping dramatically to the point where generic commodity IoT deployments are feasible. In the future, providers in high density areas, such as city centres, will be able to deploy IoT nodes with a range of sensors and make these available to clients to monitor and provide connectivity to IoT objects. The desirable situation in which IoT resources will be globally available to such clients, requires the creation of an open market for commodity IoT resources in the very same way that a market for Cloud Computing resources is emerging. Currently, managing IoT based Cloud resources is still a challenge [29]. The use of dynamic bridges, proxies and gateways allow IoT applications to be built using established Cloud Computing platforms [30]. For this to be viable, there needs to be both technical and commercial integration support. The following attempts to solidify this by highlighting the important considerations in the argument for a market for commodity IoT resources.

- **Enabling interoperability:** Enabling interoperability is a well know challenge for Cloud and IoT implementations due to the heterogeneity of both technologies. Commodity CoT resources will be used only if customers are not restricted to a specific service provider and can switch between providers due to changes in requirements or offerings. A market for trading CoT resources would encourage the development of standards and increase interoperability.
- **Creating new business values:** As the number of IoT deployments increase, the risk of a small number of providers controlling the market is high; such as is currently being observed in Cloud Computing. This increases the risk of single provider technical failures as well as single vendor lock in. Technical failures; bugs, mis-configurations and security breaches, can have a huge impact on the operations of many customers simultaneously. A CoT marketplace will enable competitive and independent implementations of CoT protocols which will greatly reduce any monopoly-related risks. Customers will also benefit by enjoying the freedom of choices from a multitude of providers.
  CoT services also require joint efforts and cooperation between businesses to bring new services to the market. A market will enable businesses to go beyond the traditional known business models to new ones such as business to business to customer (B2B2C) where the end service is traded by the adjacent industry partner who owns and manage the relationship with the end customer [31].
  Furthermore, the provision of IoT services usually requires large investments which are not affordable by most small and medium enterprises. A marketplace of commodity CoT resources will enable SMEs to be involved in a larger community. This can also attract smaller consumers with specialised needs who are best served on a retail rather than a wholesale basis. Aggregations of small providers can also form offerings from multiple CoT resource sets.
- **Improving service level agreements (SLAs):** Essential to the success of commodity CoT resources is the development of well-defined service level agreements. SLAs are currently negotiated between each provider and consumer in Cloud Computing. A market has a standard SLA which defines the minimum terms of contracts that will cover both providers and customers. Those terms are based on the characteristics of a service rather than a provider or a customer-based agreement. Both providers and customers can negotiate further terms and conditions to be included in their own SLAs without breaking the basic market SLA. A standard SLA has some benefits including better legal protection for customers and providers, better pricing policies and improved standards for market entry.
- **Enabling innovations:** A market for commodity CoT resources will add a large number of players to the current market. This will promote innovation in the required infrastructure, including IoT and Cloud technologies. This should allow infrastructure vendors to produce, market and support a wide range of differentiated products. It may also motivate the emergence of new infrastructure suppliers, and motivate innovative design and adoption of mobile sensor networks.

Although there is no standard for building CoT applications yet, this creates a unique solution for every deployment. Service providers also restrain innovations by locking-in their customers and restricting development. A market will support development by facilitating the emergence of standard interfaces.

These motivations show the many advantages to providing support for the commoditisation of CoT resources. A market will enable technical innovation through interoperability between types of CoT application. To support these goals, there needs to be a standard way of describing IoT and Cloud services. An open architecture for trading these resources with efficient algorithms that match resources provided with potential consumers of those resources would also be needed. The following section proposes a market based on multi-attribute combinatorial exchange which attempt to realise the ideas discussed in this section.

IV. A MARKETPLACE FOR COT RESOURCES

A. Overview

For the commodity IoT resources to be fully accepted and integrated with current infrastructures, they must be publicly accessible. The access method appropriate for this is using the Cloud Computing service model where consumers purchase openly available services and pay for the level of service they actually use [32]. The Cloud service model is preferable to users due to its speedy trading process and its job-oriented pricing model. Although this can be described as minimal integration CoT in the literature, it can be tailored to support other integration approaches.

As with any complex IT service, purchasing IoT services consists of many multifaceted decisions and choices. IoT resources are complex by nature and contain many types of resources. This complexity results in difficulties when quantifying their value. One possibility is to treat each task as a request for a multi-attribute bundle of resources [33]. This is an annotated list of all the required resources needed, their quantities and the required timing. This can be understood through a simple generic example of a bundle of IoT resources; $B^1 = \mathrm{L}^l\mathrm{TS}^{ts}\mathrm{D}^d\mathrm{PO}^{po}\mathrm{S}^s\mathrm{PL}^{pl}\mathrm{N}^n\mathrm{A}^a\mathrm{MV}$ defines a customer's requirements for a bundle B of resources as a Location l, Time slot ts, IoT Device d,Power po, Software s, Platform pl,Network$n$, other Attributes a and MV defining the maximum monetary value the consumer places on the resources. Resource providers can then also describe their available resources as bundles of resources, this time specifying the minimal price at which they are willing to provide the resources. For example $B^1 = \mathrm{L}^l\mathrm{D}^d\mathrm{PO}^{po}\mathrm{S}^s\mathrm{PL}^{pl}\mathrm{N}^n\mathrm{A}^a\mathrm{MV}$ specifies the available resources in similar terms, omitting requirement specific information.

In the CoT marketplace, a contract with well defined SLA between provider and consumer should be subjected to certain constraints such as cost of resources and time of utilisation. This should be a simple foundation of a CoT trade system which would be more complicated in reality. To optimally match resource providers and consumers, there is a well-known resource matching optimisation problem [34]. This is done using intermediary brokers who maintain a list of resource requests and offers, matching them if possible. The proposed marketplace is based on combinatorial marketplaces [33] and auctions [35] due to their ability of controlling and optimising the matching process.

For this to be viable, a consistent vocabulary for defining CoT resource attributes is necessary. A dynamic market architecture needs to also exist to fairly and efficiently match these resource bundles. Section IV-B introduces a vocabulary for describing generic IoT example but can be customised to accommodate specific scenario requirements. Section IV-C presents an architecture for trading CoT resources as a commodity. Section IV-D describes the algorithmic support for the auction mechanism underpinning the proposal. Section IV-E summarises the proposal.

B. Vocabulary

The Vocabulary for multi-attribute bundles for CoT resources includes the following attributes. These are the fundamental building blocks of a generic CoT offering that will be published by the provider in order to specify the nature of available resources. Similarly, potential consumers will publish their requirements in terms of these attributes, in order to specify their data and quality of service requirements. An efficient scenario is one where all consumers bundle requests are met by the available provider resources within a reasonable cost V. To achieve this requires the matching of consumer bundles with provider bundle. The above mentioned attributes are a short list for proof of concept only. In reality, a full functioning marketplace is expected to have further detailed attributes as integral part of its vocabulary.

- **Location L** As IoT objects are inherently location-sensitive, any application needs to be able to define its physical scope. The location attribute will be used by a resource provider to specify the exact GPS location of the sensor in the case of a static sensor, or a region in which the sensor is located if mobile. The consumer would specify a broad location within an area which enables matching with a suitable sensor. IoT devices with well defined locations can benefit from nearest connected Cloud in terms of faster data aggregation and back-end processing.
- **Time Slot TS** This describes the lease time required by the consumer. This includes single time slot and set of all time slots required [36]. In CoT scenario, it is critical for resource bundles to be associated with accurate time slots to be traded in or released to be idle or leased again by other consumers.
- **Device D** Device attribute aims to define the hardware component of IoT (e.g sensor, motes, actuator). This is to address the hardware capabilities for collecting and transmitting data. The Device attribute will also identify the processing power of the device in a standard unit such as clock speed or instructions per second and any storage capacity available for the device.

- **Power PO** Power requirements are important as this defines the operational constraints, e.g., a battery-powered devices cannot constantly transmit data as a live feed indefinitely. This attribute can simply be specified in power consumption under specified circumstances and application power requirements.
- **Network N** The Network attribute can be described as a utility including speed, latency, error rate and drop-out rate. Potential consumers would specify this attribute in terms of minimum level of service appropriate for their application. The network technology used is also described under Network attribute including WiFi, Bluetooth, USB, GSM, ZigBee, RF and GPS [37]
- **Software S** If the CoT resources bundle consists of a software, then related properties should be listed under Software attributes. This may include software type (e.g open source or proprietary), software license (e.g free or paid), availability of support/updates and available functions of software.
- **Platform PL** CoT resources can be developed and deployed to support single or multiple platforms. Platforms supported should include mobile OS (e.g Android and IOS) and non-mobile OS (Windows, Unix, Linux and Mac OSX).
- **Security S** Publicly available resources require security to be considered. Some resources may require a higher level of security than others (e.g., due to cost, or strategic reasons). Resource consumers will have different requirements of security, depending on their intended use of the resource; particularly if resources should be accessed exclusively by one consumer.
- **Other Attributes A** CoT resources should be offered as dynamic and flexible bundles. Wide range of attributes are needed to identify resources making them ready to be traded. Each CoT deployment is expected to bring its own specific attributes. In reality, CoT marketplace should keep adding new attributes extending its vocabulary to enable any Cloud or IoT resources to be traded.

C. Architecture

To achieve the goal of a market for CoT resources, they must be able to be integrated with the current state-of-the art in applications. The trend is towards more service-oriented application architectures taking advantage of Cloud Computing paradigms. There are many competing definitions of exactly what constitutes Cloud Computing [38], however, a broad consensus suggests that all Cloud Computing platforms include: abstracted or virtualised resources, elastic resource capacity, programmable self-service interface and usage-based pricing model. For IoT resources to become a first class entity in the Cloud they need to begin taking on these properties. Figure 1 illustrates the a conceptual architecture designed to meet these principles.

The physical components are connected through Internet gateways. Both providers and consumers submit their offerings or requests to the Resource Manager using a web portal. The Resource Manager filters offerings or requests to

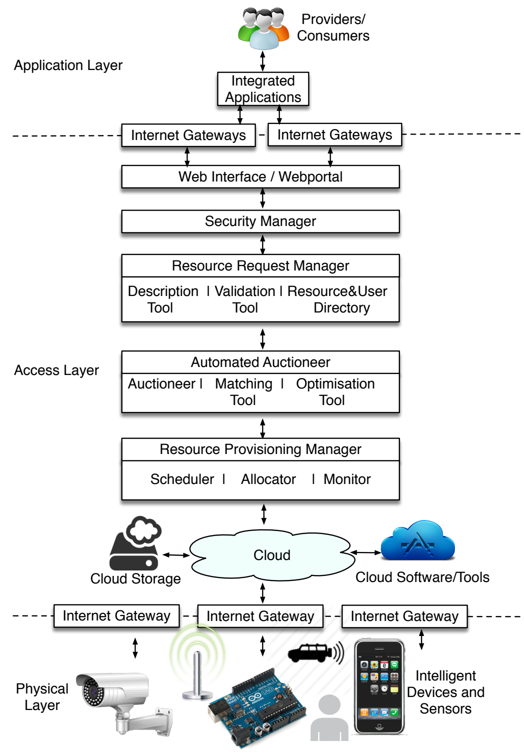

Fig. 1. Conceptual Model of the Proposed Architecture

match the marketplace standards and requirements. Accepted offerings are admitted to the Resource Directory and kept synchronised with their owners' profiles. Buyers search for resources using web interface of the Resource Directory that has an index of all resources available with their associated attributes. Using the Automated auctioneer, buyers choose the required resources with specific attributes and submit bids for them. The auctioneer searches for a match with the available offerings and forms the best bundle of resources possible. After payment is made, the auctioneer escalates that bundle to the Resource Provisioning manager that acts as backbone of access to the required resources. The Manager coordinates between the allocator and the scheduler to provide dynamic provisioning. The allocator is responsible for joining and dis-joining the resources according to the lease time assigned by the scheduler. The scheduler is also handling assignments of tasks in the Cloud applications and storage. It schedules tasks related to processing, analysing, visualising and storing data generated by sensors.

D. Auction Process

To support this architecture, consumers need to be matched with providers using a bundle matching algorithm. The problem is non-trivial, involving multi-attribute consumer and provider bundles. These algorithms have been used to support combinatorial exchange problems in Cluster Computing [35], Grid Computing [34] and Cloud Computing [32] applications.

In the approach here, adapted from combinatorial auctions in Management Science [39], the role of the marketplace M, is to efficiently match resource providers R with a set of bids for resource bundles B from resource consumers C. A bundle B is a combination of resources from a provider P such that $B \subseteq R$. A consumer C can bid for any subset of R. Assuming that B_i is a set of bids $b_i = b_1, b_2, b_3, ..., b_n$. A bid is a tuple $B_i = (B_i, p_i)$ where $B \subseteq R$ is a set of resources and $P_i \geq 0$ is a price. Each resource R is supplied by P to C at a value V.

The providers P submit their resource offerings to the market and the resource consumers C submit request bundles B to the market. These form the pool of CoT resource offerings and requests. The task for the Resource Request Manager is to fulfill as many consumer resource requests as possible by efficiently matching providers to consumers. The aim of this process depends on the aims of the market; the following matches based on maximising the profit for the provider by choosing the highest consumer bid for the resources is the winning bid Wi.

$$Wi = \sum_{r=1}^{n} MaxPi(r)$$

To minimise the overall cost to the consumers as a group, or to fulfill as many requests as possible it is desirable to minimise the overall cost to the consumers as a group. The following illustrates the case where the winning bid Wa is the sum of the max bids over the number of max bidders (consumers).

$$Wa = \frac{\sum_{i=1}^{n} Max(bi)}{\sum_{i=1}^{n} C_i}$$

This will distribute the cost amongst consumers, reducing the overall cost and enhance the vision of enabling shared access to CoT resources. The consumers will pay the average of their bids. Another way to minimise the overall cost to the consumers while giving the providers with most preferable price, is by evaluating a range of maximum and minimum bids. The consumers submit minimum and maximum bids while the resource is assigned with minimum acceptable price. The following shows the case where the winning bid Wa is the average of sum of the averages of all minimum and maximum bids.

$$Wa = \frac{\sum_{i=1}^{n} (avgmin(bi) + avgmax(bi))}{\sum_{i=1}^{n} bi}$$

The above wining bid has not to drop below the minimum acceptable price set by the provider. Moreover, this widens auctioning process to include larger number of bidders for shared resources . Different matching algorithms can be used to support the process of matching depending on the market requirements.

E. Summary

Internet of Things resources have to be accessible publicly so integration with Cloud can be achieved. The integrated CoT resources can then be traded as standard Cloud services. A conceptual model of multi-attribute combinatorial marketplace is proposed in this section. The use of combinatorial approach in this case is justified by its natural ability to solve similar complex problems (e.g. [40]). The complexity resides here due to the diversity of Cloud and IoT resources that results in difficulties when quantifying their value. The use of bundles is argued to overcome these complexities in trading CoT resources. A consistent vocabulary and notation for describing the attributes of CoT resources are required. A generic list of basic vocabulary and notation of CoT resources are defined in this section. A marketplace of CoT resources should maintain a dynamic dictionary of vocabularies and notations to accommodate all possible attributes of any CoT resources. A simple and open architecture for CoT marketplace is presented and described. Although this architecture can be categorised into ”minimal integration” strategy in the literature, it can be tailored to support other CoT integration approaches (e.g. partial and full integration). Basic building blocks of a generic CoT offering is also proposed and explained in this section. A CoT marketplace should contain much advanced algorithms in reality to describe all processes of trading CoT resource. The overall proposal supports commoditisation of CoT resources and shows that using a multi-attribute combinatorial exchange approach to trading CoT resources as a commodity is viable.

V. CONCLUSIONS

This paper has argued for the need for a market for CoT resources. It has proposed a multi-attribute combinatorial market for commodity IoT resources. It has defined a vocabulary which enables CoT resources to be consistently described by resource providers and consumers. The paper presented an architecture and associated trading algorithms which allow resource providers and consumers to trade resources. The architecture enables the on-demand access to resources for CoT applications. Future work will realise the architecture for several case studies and focus on the performance of the market-trading algorithms with various CoT architectures.

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