Enabling Commodity Environmental Sensor Networks Using Multi-Attribute Combinatorial Marketplaces

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***Abstract*—Large scale distributed e-infrastructures are emerging as commodity resource platforms. The next generation of commodity e-infrastructures will encapsulate the physical or tangible world by integrating ubiquitous sensors. Cheap environmental and physiological sensors are being increasingly deployed by many commercial organisations. The process of discovering and accessing commercially available resources requires a market for providers and consumers to trade these resources. This paper argues that developing a market will encourage the commoditisation of environmental sensor networks. It presents an overall architecture and adopts algorithms to support the trading of commodity environmental sensor networks.**

I. INTRODUCTION

Increasingly, Information Technology (IT) resources are being considered commodities and not organisational assets. As the price of these resources has decreased, availability has increased and third party organisations have taken over the provision of some IT services. This is most pronounced in the provision of web based services with backend processing that are now largely hosted in large-scale data centres. The emergence of Cloud and Utility Computing, which provides a consistent pricing and access model for accessing infinite global IT resources, has further accelerated this phenomenon. The commoditisation of IT should result in overall decreased prices, an increase in the numbers of services, and improved performance of services as a whole [1].

As yet, the commoditisation of IT infrastructures is wholly based around the provision of traditional enterprise applications [2] such as customer relationship management, supply chain management and enterprise resource planning. These are inherently software based solutions, similar architecturally in that they make use of database backends, flexible computational services and web-based front-ends to support enterprise applications. It is suggested that over time, the commoditisation of IT infrastructures will be extended into the physical or tangible world [3]. It is feasible for physical resources to take part in the "commodity-utility" IT resource world, through internet connected sensors and actuators. This will enable the Internet of Things [4] which depends on the wide availability and integration of sensors and the Internet.

Both the academic and commercial sectors are rapidly developing a wide range of sensors, sensor network and wireless sensor network technologies. Development of hardware has included the low-cost sensors, low-power radios [5] and the mote packages that encapsulate them. To support these hardware platforms, a complete stack of software has been developed, including special purpose Operating Systems [6], [7] to support low-power and small footprint platforms, and networking protocols [8], [9] to support low power devices. There has also been development in specialised middleware technologies [10], [11], [12], allowing applications to be built more efficiently, and high level application paradigms [13], [14] to support efficient application development.

Currently, environmental scientists and engineers are major users of sensor network technologies [15]. There are a large number of sensors and sensor network technologies that can measure the environment at specific points in time, over periods of observation, across a range of physical locations. The environment can be measured as part of day-to-day operation (for example, air conditioning units) or to observe disasters such as flooding of rivers [16] and oil spills [17].

For the commoditisation of environmental sensor network 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 marketplace to trade these resources. Cloud Computing market places are only just emerging, but are not used by the majority of consumers; inevitably, a market will also emerge for environmental sensor networks. This paper proposes an architecture for trading commodity environmental sensor networks based on multi-attribute combinatorial exchange. It shows how this approach can support generic sensors and applications.

The remainder of this paper is structured as follows. Section II provides a background of the use of sensors and environmental sensor networks. Section III motivates a marketplace for enabling a market for environmental sensor networks. Section IV defines an architecture and notation for this. Section V analyses its usage in a realistic case study. Finally Section VI presents some conclusions.

II. Environmental Sensor Networks

Environmental 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 environmental sensors, collate, aggregate and transfer this to backend computers for processing. This data is used to support the analysis of current and historic environmental conditions. To support this, are advances in hardware platforms, low-power radios, operating systems, network protocols and applications.

The choice of mote package depends on the target domain and factors such as power supply availability. Mote designs for situations such as air conditioning systems are generally customised commercial solutions. As the requirements become more specific, such as monitoring pollution levels at remote sites, bespoke solutions are needed e.g. using low-power ARM based solutions. Increasingly, embedded micro-controllers are being used to provide extremely low power solutions at very low relative cost. This is driven by the availability of prototyping platforms such as the Atmel-based Arduino platform.

There is an increasing number of sensors of which sensor platforms can take advantage. These include the simplest resistance-based sensors (such as temperature, pressure and light), more complex digital sensors (for supporting complex tasks such gas monitoring) and packages of sensors using I^2C buses. There is also an increasing array of actuators, including simple power switches and more complex systems like air conditioning and building temperature control systems. Sensors exist to support most application domains required by environmental engineers.

Complementing this range of mote and sensor options are different options for connecting them to each other and to base stations. For long-range communication, RF and directional WiFi can be used to support applications such as mine-site or transport monitoring. In the mid range, WiFi, bluetooth and wired communications support local interconnection of sensor motes. Low-power [5] radios support communication between these platforms at very low battery cost and short range. Networking protocols such as 6LowPAN [8] and uIPv6 [9] have been developed to support low power devices.

A complete stack of software has been developed to support and complement sensor network mote platforms. Operating Systems such as TinyOS [6] and Contiki [7] have been created to support low-power and small-footprint platforms. Middleware such as OpenCOM [10], NesC [11], LooCI [12] and application paradigms such as Kairos [13] and TinyDB [14] have also been developed.

In response to increased demands for sustainability, and as buildings become more complex, integrated systems, sensor networks are increasingly being used to observe, monitor and control heating, ventilation and air-conditioning systems [18]. In new commercial buildings, monitoring and control systems are, as a rule, included as a necessary part of the construction. Other monitoring systems are becoming more common, including: smart grids, distributed and embedded renewable energy generation, water harvesting and waste-water recycling, solid and liquid waste resource recovery reprocessing and distribution back into energy and manufacturing.

Environmental Science depends heavily on sensor networks for monitoring a large range activities and systems [19]. These are driven by three major factors; to reduce the cost of environment maintenance, to improve quality of life for the people inhabiting the environment, and to adapt to a world that places an increased focus on sustainability and green issues. Environmental sensor networks are being used to support the monitoring of both natural and human environments. Low cost sensor networks may be fundamental to achieving sustainable development, particularly in the area of carbon emissions.

Sensor-networks are being deployed to support computational models of flooding [20], pollution [21] and hurricanes [17]. Unfortunately, there is little or no support for computational elasticity for sensing applications which is required in order to deal with environmental dynamism in the face of emergency events Subsequently, emergency situations such as the April 2010 oil spill in the Gulf of Mexico necessitate manual re-tasking of computational facilities together with application refactoring [17]. The increasing requirement to monitor the environment and the dynamic computing environment in which it exists, will lead to the commoditisation of environmental sensor networks in a similar way to the commoditisation of IT is being achieved by the pay-per-use models of Cloud and Utility computing.

The provision of sensing resources in the Cloud extends the current domain of Cloud Computing to the physical or Tangible Cloud [22]. As first class entities in the Cloud, sensor network devices can be used together with 3rd party Cloud resources. For example, the developer of an environmental monitoring and modelling application might compose sensing resources from the Tangible Cloud with storage and computational resources from the traditional Cloud.

III. Motivation

The rapid growth of environmental sensor networks has led to a very large number of providers of hardware and software platforms. The costs of building and deploying sensor networks are dropping dramatically to the point where generic commodity sensor network deployments by commercial providers is feasible. In the future, providers in high density areas, such as city centres, will be able to deploy sensor networks with a range of sensors and make these available to clients who might want, or need, to measure, for example, pollution, footfall or rainfall. The desirable situation in which sensor resources will be globally available to such clients, requires the creation of an open market for commodity environmental sensor networks in the very same way that a market for Cloud Computing resources is emerging. The use of bridges and proxies will allow applications that utilise sensors to be built using established Cloud Computing platforms [23]. 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 sensor networks.

1. **Enabling interoperability:** Commodity environmental sensor network resources will be utilised only if customers are not restricted to a service provider and can switch between providers due to changes in requirements or offerings. Existing sensor networks are largely incompatible, with each

using distinct hardware, software and network approaches to achieve its goal. A market for trading environmental sensor networks would encourage the development of standards and increase interoperability.

2. **Empowering small and medium enterprises (SMEs):** The provision of environmental sensor network services usually requires large investments which are not affordable by most SMEs. A marketplace of commodity environmental sensor networks 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 environmental sensor networks.

3. **Improving service level agreements (SLAs):** Essential to the success of commodity environmental sensor networks is the development of well-defined service level agreements. SLAs are currently negotiated between each provider and consumer. 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, and improved standards for market entry.

4. **Avoiding monopoly:** As the number of environmental sensor network 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, misconfigurations and security breaches, can have a huge impact on the operations of many customers simultaneously. A marketplace will enable competitive and independent implementations of environmental sensor networks which will greatly reduce any monopoly-related risks. Customers will also benefit by enjoying the freedom of choices from a multitude of providers.

5. **Enabling infrastructure innovation:** A market for commodity environmental sensor networks will add a large number of players to the current market. This will promote innovation in the required infrastructure, including sensors, motes and network 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 to and adoption of mobile sensor networks.

6. **Enabling application and platform innovation:** There is no standard for building environmental sensor network applications, even for those in the same application domain. This creating 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 there are many advantages to providing support for the commoditisation of environmental sensor network resources. A market will enable technical innovation through interoperability between different networks. To support these goals, there needs to be a standard way of describing sensors and sensor networks. There also needs to be an open architecture for trading these resources with efficient algorithms that match resources provided with potential consumers of those resources. The following section proposes a market based on multi-attribute combinatorial exchange which attempt to realise the ideas discussed in this section.

IV. A Market for Commodity Environmental Sensor Networks

A. Overview

For the commodity environmental sensor networks 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. As with any complex IT service, purchasing environmental sensor network services consists of many multifaceted decisions and choices. Environmental sensor network resources are, by nature, complex, in that they contain many types of resources. The 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 [24]. This is an annotated list of all the required resources needed, their quantities and the required timing.

This can be understood through a simple example; $B^1 = L^l T^t M^m S^s C$ defines a customer's requirements for a bundle B of resources as a Location l, required Time t, Sensor Motes m, Sensors s and C 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 $B^1 = L^l M^m S^s C$ specifies the available resources in similar terms, omitting requirement specific information.

In an open market place, if a provider can supply the necessary resources within certain constraints such as cost, then a contract can be made between the consumer and provider with a given SLA. It is of course, more complicated than this in realty, but this is the simple foundation of such a system. To optimally match resource providers and consumers is a well-known resource matching optimisation problem [25]. This is done using intermediary brokers who maintain a list of resource requests and offers, matching them if possible. Combinatorial market places [24] and auctions [26] offer the ability to control and optimise the process of matching consumers and providers.

For this to be viable, a consistent vocabulary for defining commodity environmental sensor network attributes is necessary. A market architecture needs to also exist to fairly and efficiently match these resource bundles. Section IV-B introduces a vocabulary for describing Networked Sensors services. Section IV-C proposes an architecture for trading environmental sensors 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 commodity environmental sensor networks includes the following attributes. These are the fundamental building blocks of wireless sensor networks 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 C. To achieve this requires the matching of consumer bundles with provider bundle.

- **Location L** As environmental sensor networks 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.
- **Sensor S** The fundamental component of an environmental sensor network is the sensor (e.g., temperature or pressure). This will be a combined value that specifies the properties of Sensors; including the type of sensor, its mechanics (Resistance or I^2C), its range (0C to 30C for a temperature sensor) and transmission properties such as transmission interval.
- **Motes M** To enable the collection and transmission of sensor data, sensors are hosted on boards, commonly embedded micro-controller based, called motes. The Mote attribute will identify the processing power of the device in a standard unit such as clock speed or instructions per second. It will also denote other features such as the amount and accuracy of Analog-to-Digital converters available to the Mote.
- **Power P** Power requirements or ability are important as this defines the operational constraints, e.g., a battery-powered mote cannot constantly transmit a live sensor feed indefinitely. This attribute can simply be specified in power consumption under specified circumstance 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.
- **Access Characteristics A** Any sensor platform will use specific general or domain-specific programming interfaces; these would be described by this attribute, thus allowing, and providing the mechanisms for, the consumer to interact with the sensor network.
- **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.

C. Architecture

To achieve the goal of a market for environmental sensor networks, 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 [27], 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 environmental sensor networks to become a first class entity in the Cloud they need to begin taking on these properties. Figure 1 illustrates the proposed a conceptual architecture designed to meet these principles.

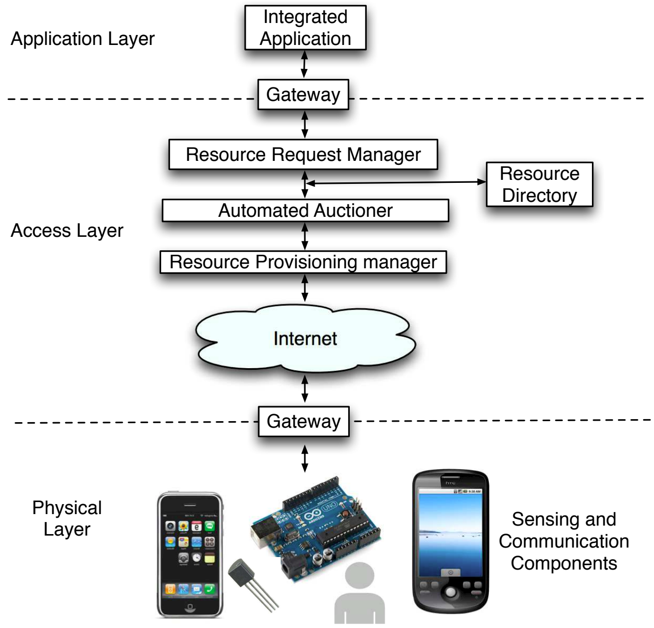

Fig. 1. Conceptual Model of the Proposed Architecture

The physical sensing components are connected via internet to a gateway. Both providers and buyers submit their offerings or requests to the Resource Manager that filters them to match the marketplace standards. Accepted offerings are admitted to the Resource Directory. Buyers search for resources using 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 is responsible for allowing the buyer to access the required bundle.

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 [26], Grid Computing [25]and Cloud Computing [28] applications.

In the approach here, adapted from combinatorial auctions in Management Science [29], 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 resource offerings and requests. The task for the market is to fulfil 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 fulfil 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).

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

This will distribute the cost amongst consumers, reducing the overall cost. The consumers will pay the average of their bids. Different matching algorithms can be used to support the process of matching depending on the market requirements.

E. Summary

This section has proposed a multi-attribute combinatorial market for commodity environmental sensor networks. It has argued for the use of bundles for trading environmental sensor network resources. It defined a consistent vocabulary and notation for describing wireless sensor networks. It proposed a simple and open architecture for trading environmental sensor network resources. It also discussed the market trading algorithms required to support the architecture. These proposals will enable the commoditisation of environmental sensor networks. This support shows that the proposal of using a multi-attribute combinatorial exchange approach to trading sensors as a commodity is viable.

V. Case Study

This section describes a case study which would be enabled based on the architecture introduced in Section IV. The case study chosen imagines a high-traffic metropolitan area of a major city. It is conceivable that such a location might be desirable to be observed by many governmental and commercial organisations, interested in public footfall. To understand this case study in the context of this paper, the provider resources, consumer usage and matching algorithms will now be discussed.

A. Provider Resources

In this case study, a sensor network provider deploys a large network of public footfall sensors across the metropolitan area of a city. The network consists of a number of motes that each have attached a small number of road-side footfall sensors that sense the number of people walking on the pavement/sidewalk. These motes are connected via a city area wifi network which has, at various access points, wired connectivity to the internet. The following characterises this scenario in terms of the vocabulary defined in Section IV-B.

- The *Location* as an absolute GPS location. It is assumed that this would not change during deployment. To support many resources in a very localised area, this must be a high resolution GPS location.
- The *Sensors* available on the mote is, at its most basic, just the footfall sensor.
- The *Mote* attribute describes the processing power of the Mote in MIPS.
- The *Power* attribute describes the Mote power as continuous as it is powered by mains power.
- the *Network* attribute describes the network characteristics as 7 out of a scale of 10 as it is on a reliable but still wireless connection.
- The *Access Characteristics* attribute specifies that access is through pull web service interface calls.
- The *Security* attribute specifies that the connection is using SSL for the web service interface call.

B. Consumer usage

The consumers of the resources will use them for a wide variety of applications. The three main classes of envisaged applications are marketing, safety and environmental monitoring. Examples of each of these can be described using the vocabulary defined in Section IV-B.

Direct Individual advertising and marketing A marketing agency can use footfall statistics to sell electronic billboard advertising space at appropriate prices to clients. Combining these data with data from other sources such as public transport timetables or retail occupancy, will allow the agency to create, and charge for, dynamic advertising packages for their clients based around the number of people passing a given location at a given time. The agency, in this case the consumer, would request a resource bundle specifying a location, for example on a street corner, as many footfall sensors as available, undefined mote processing power, constant power and network access, and with web service encrypted access.

Public Monitoring and Control Footfall is a good indicator of pedestrian activity in a given area at a given time. As such, monitoring footfall allows crowd analysis to model public emergencies. Using this architecture, local government can gain high priority access to sensor resources for short periods of time. For prediction, the resource request would be for sensors in a general location, with footfall sensors and limited power, network, access and security characteristics. For live emergency event monitoring, the maximal possible resources at the most reliability possible would be requested.

Environmental Impact Analysis Distributed environmental sensors are especially appropriate at supporting environmentally focussed applications. Footfall data can be combined with pollution and transport data to gain a detailed picture of the environmental impact of activity in the area. As these types of analysis are usually poorly funded and with limited access to data, a bundle request would be submitted with just a request for any footfall sensor at the lowest possible price.

C. Discussion

The notation and algorithms proposed in Section IV support the efficient trading of resources for this case study. A major challenge exists in dealing with contention for the available resources. For most sensing applications, multiple consumers accessing the resources will not be a problem. However, for some applications, such as those requiring in-situ processing, or those that are being sought in order for a consumer to gain some competitive advantage, an exclusivity of access to resources may be required. Thus, the trading algorithm, needs to deal with an additional exclusivity parameter from resources consumers. The general issue of resource contention will probably be solved with normal market forces - the highest bidder will get the resources. With enough contention, it is expected that further resources can be provisioned.

VI. Conclusions

This paper has argued for the need for a market for the emerging area of commodity environmental sensor networks. It has proposed a multi-attribute combinatorial market for commodity environmental sensor networks. It has defined a volcabulary, architecture and market-trading based algorithms to support this proposal. It has used a case study to illustrate the applicability of the approach. Future work will realise the architecture for several case studies and focus on the performance of the market-trading algorithms with various environmental sensor network architectures.

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