System Architecture Directions for Tangible Cloud Computing

Kevin Lee
School of Information Technology
Murdoch University
Murdoch 6150, Western Australia
kevin.lee@murdoch.edu.au

Danny Hughes
Department of Computer Science
Xi'an Jiaotong-Liverpool University,
Suzhou, China
daniel.hughes@xjtlu.edu.cn

Abstract—**The field of wireless sensor networks has produced a range of supporting hardware and software technologies that facilitate the creation of sensor network applications. Despite these advances, the implementation of wireless sensor network applications remains a complex task that requires domain experts and a significant investment of time and money. This level of investment is often infeasible for single applications, especially for those applications with a short life-cycle. This paper suggests a new direction in wireless sensor network research. We argue that next generation sensor network platforms should strive towards a shared infrastructure, multi-application paradigm, with a clean separation of concerns between infrastructure providers and application developers. These are principles that are well established in the field of Cloud Computing. This paper introduces our vision for future sensor networks, which we refer to as the 'Tangible Cloud'. To support this vision, we introduce a reference architecture and pricing model for sensor network resources.**

Keywords: Wireless Sensor Networks; WSN; Cloud Computing

I. INTRODUCTION

Cloud Computing has emerging as a global platform which offers open access to extensible computational, storage and software services. These resources are typically publicly available and subject to an open pricing model. There are two key benefits of for users of Cloud Computing. Firstly, Cloud Computing removes the need for those working in the application space to create and manage their own supporting infrastructure. This reduces initial costs and start-up time. Secondly, the elastic fashion in which Cloud Computing resources are provided allows supporting infrastructure to be scaled up or down as required by the application developer.

Computer infrastructure resources are offered in the Cloud using a model known as 'Infrastructure as a Service' (IaaS). Examples include Amazon EC2 [1] and Slicehost [2]. Infrastructure services are provided from a common pool of heterogeneous resources that are transparently shared amongst users using virtualization technologies such as Xen [3]. Cloud Computing Resources can also take the form of a complete supported environment, known as 'Platform as a Service' (PaaS) [4] [5] for the deployment of individual applications. This model is well suited for the majority of applications that demand elasticity, flexibility and redundancy, without requiring low-level control of the supporting infrastructure. The final model of resource provision used in Cloud Computing is 'Software-as-a-Service' (SaaS) [6] which provides online, subscription-based access to software.

A key drawback of current Cloud Computing models is that they do not allow for interaction with the physical world. This precludes use of the Cloud model in a large number of application domains such as environmental monitoring [7], medical computing [8] or industrial automation [9], all of which rely on input data gathered by sensors and responses delivered by actuators. To illustrate this problem, consider the following motivating example: an industrial park contains two pieces of deployed WSN infrastructure: (i) a traffic-tracking network deployed in vehicles and (ii) a physical storage monitoring sensor network deployed in a warehouse. These two pieces of infrastructure each require significant investment and must be maintained by local experts. The owners of the infrastructure may wish to commercialize redundant resources by offering them to 3rd parties using the Tangible Cloud. In this fashion, 3rd parties could use these resources to provide location-aware services. To support scenarios such as these, this paper proposes the unification of two young but growing subject areas: Wireless Sensor Networks and Cloud Computing. To support this we provide a reference architecture for the Tangible Cloud and apply this to a number of case studies.

The remainder of this paper is structured as follows. Section II introduces the vision of the 'Tangible Cloud', the separation of infrastructure and application concerns and deployment scenarios. Section III describes the proposed architecture for Tangible Cloud Computing and the core supporting technologies needed for this vision. Section IV presents some conclusions and Section V discusses directions for future work.

II. THE TANGIBLE CLOUD

There are many definitions of what constitutes Cloud Computing [10], however, broad consensus exists that the features of Cloud Computing include:

1. Abstracted or virtualized resources.
2. Elastic resource capacity.
3. Programmable self-service interface.
4. Pay-per-use pricing model.

As described in Section I, the common classification for infrastructure-centric Cloud services is as either Infrastructure as a Service (IaaS), Platform as a Service (PaaS) or Software as a Service (Saas). An IaaS service provides computational and storage resources with some basic service support (e.g. common database provision). In contrast, PaaS provides a full application development, deployment, distribution and support environment. SaaS provides fully developed, online, subscription-based access to software.

The Tangible Cloud extends the current domain of the Cloud to include the physical world. This means that networks of physical devices should be able to expose their functionality as standardized Cloud services. As first class entities in the Cloud, devices in the Tangible Cloud can also be used together with 3rd party cloud resources. For example, the developer of an environmental monitoring and modeling application might compose together sensing resources from the Tangible Cloud together with storage and computational resources from the traditional Cloud.

In order to support the sharing of WSN resources amongst multiple users, lightweight virtualization technologies are required. In addition, to enable this vision, physical devices and networks need to expose their functionality to 3rd parties using open Web Service standards such as WSDL, SOAP and UDDI [11]. The use of open interfaces will enable Tangible Cloud resources to be used with established cloud tools such as [12] and [13], open Cloud platforms such as [14] and [15] as well as promoting interoperability with existing WSN systems.

Another key requirement for the Tangible Cloud is the availability of a programmable self-service interface and pricing model. This will allow 3rd parties to easily purchase Tangible Cloud resources for use in their applications.

The remainder of this section discusses key concerns for the Tangible Cloud including (i) ensuring a clean separation of concerns and (ii) deployment scenarios. Section III then introduces an architecture that addresses these concerns.

A. Clean Separation of Infrastructure and Application Concerns

WSN are composed of highly specialized devices which are subject to extreme resource and power constraints [12]. Given these complexities, the first generation of WSN infrastructure followed a design methodology that was highly optimized for a specific application [12] [7]. This tight coupling left little scope for the sharing of WSN infrastructure between multiple applications. The approach followed by the second generation of WSN infrastructure is more flexible and reusable. Platforms such as Sun SPOT [13] and Sentilla [14] provide general purpose sensing platforms that may be programmed using standard languages such as Java [15]. At the hardware level, this provides a more promising base to support the virtualization of resources.

Most recently, lightweight run-time reconfigurable component models have emerged as a promising platform to support the sharing and re-use of WSN resources [16] [17]. The encapsulation of WSN resources in a component with well defined interfaces makes it easier for 3rd parties to discover and use these resources. It also allows for the possibility of automated resource management [18]. In systems such as these, the role of the application developer becomes the composition of these reusable resources into coherent application compositions.

By separating the concerns of infrastructure development and by integrating sensor networks in the cloud computing space, the domain-specific application developer is free to focus on creating the application itself. Thus, the WSN engineer and the application engineer can both concentrate on their specializations, resulting in a better quality of application.

B. Tangible Cloud Deployment Scenarios

Scenarios in the Tangible Cloud could theoretically involve any networked embedded device. The model, however, naturally lends itself to scenarios where devices provide generic and reusable sensor data such as temperature, light, humidity and location. This kind of data access, which has many potential consumers, could be provided as a useful service to multiple applications for little additional cost. Two archetypal scenarios are provided in the following sections.

1) Scenario 1: City-Wide Population Tracking

One such scenario involves a citywide sensing infrastructure deployed to enable the monitoring of population movement in real-time. Such an infrastructure would involve deploying many sensors on roadside walkways, public areas and large buildings.

There are many potential users of such a deployment, all of whom compete for access to the shared resource. This may include: advertisers wanting to know popular areas of public activity, disaster management organizations to monitor population movement and emergency services to monitor ongoing events for policing. The following advantages would be available to multiple user groups;

- Advertisers can pay for access to pedestrian and car traffic data to position advertisements effectively.
- Emergency Services can use the available data to plan emergency incident response and even track live events.
- City Planners can use traffic data to direct road and walkway funding policy

In a traditional market, the deployment of such sensors would involve a single organization having to meet the entire cost of deploying and maintaining such an infrastructure, which is often infeasible for single applications. The cloud allows many potential users to pay for access to shared resources, thus making large-scale WSN resources more economical.

2) Scenario 2: Warehouse Monitoring

A scenario that would benefit from the tangible cloud model is that of large scale warehouse monitoring. A warehouse consists of multiple storage bays where containers may be stowed prior to transportation. During its journey, a shipping container may pass through several warehouses owned by different providers, each of which has installed their own tracking and environmental monitoring sensor network.

The advantage of exposing these facilities using the tangible cloud model is that it is possible for the owner of a particular shipping container to easily track its progress through third-party infrastructure using the infrastructural services that these providers expose to the tangle cloud.

- Customers of the shipping company, may use this system to track their shipments precisely.
- The shipping company may perform advanced supply chain optimization using up-to-date warehouse capacity data.
- The warehouse owner is provided with an additional source of revenue through the provision of value added services to customers that demand end-to-end tracking.

C. Discussion

The feasibility of the motivating scenarios presented in Section II.B is highly dependent upon the availability of an open and shared WSN infrastructure. While no individual user of either system could justify the entire cost of system deployment, maintenance and management, the shared infrastructure model makes large scale multi-purpose sensor networks significantly more feasible.

A key feature of the warehouse monitoring scenario is that increased scale is achieved not through a monolithic infrastructure deployment, but through the virtualization of multiple underlying sensor networks using common technologies.

Perhaps the most important feature of the proposed model is that it allows each party to contract around its area of core competence. The infrastructure provider and manager do not consider application-level services and conversely, the application developer does not consider the complexities of WSN deployment and maintenance.

III. TOWARDS A REFERENCE ARCHITECTURE FOR THE TANGIBLE CLOUD

This section provides a reference architecture for the tangible cloud. Section III.A reviews promising supporting technologies. Section III.B discusses models of service provision for the Tangible Cloud. Finally, Section III.C provides an architectural model of the Tangible Cloud.

A. Supporting Technologies

A successful architecture for the integration of WSN and Cloud Computing must anticipate the differing needs of: (i.) generic component developers, (ii.) infrastructure owner-managers (iii.) application composer-managers. The problem of providing adequate programming abstractions to support this spectrum of requirements is explored in detail in [16] and is summarized in brief below.

Generic Component Developers require common distribution and reconfiguration services that abstract over the low-level details of system implementation to provide common support for code distribution, execution and reconfiguration. Lightweight run-time reconfigurable component models such as OpenCOM [17] and LooCI [18] provide these services while promoting the re-use of functionality through concrete interface definitions.

Infrastructure Owners and Managers require support for the high level specification of policies that can act at the granularity of entire networks, groups of nodes or individual resources. These features may be served by a light-weight policy-based management architecture such as PMA [19] together with billing support and a pricing model for the services they expose in the Tangible Cloud.

Application composers and managers require support for the high level composition of tangible could resources into consistent applications. This requires standards-based support for resource discovery, standardized binding mechanisms and high level application composition tools, such as those available in the field of Model Driven Software Engineering [20].

B. Models of Service Provision

As with other Cloud systems, some application scenarios require access to low-level system functionality, while other scenarios may be adequately served by generic high-level support. These are best served as by Infrastructure as a Service (IaaS) and Software as a Service (SaaS) models respectively. Section III.B.1 and III.B.2 discuss how these service models may be realized in the WSN domain. In addition to providing directly usable services, the Tangible Cloud can also be used to provide a supported platform for building services, called Platform as a Service (PaaS), this is discussed in section III.B.3.

1) Tangible Infrastructure as a Service (TIaaS)

The provision of Infrastructure as a Service basically amounts to the leasing of a concrete set of infrastructural resources and supporting tools. For Cloud Services operating on the resource rich back end, virtualization services such as Xen [3] allows for the sharing of powerful computing resources among many potential users. However, in the resource-scare sensor network environment, the role of virtualization is different. It is infeasible to share the low level services of a single sensor node between multiple users and hence the role of virtualization is instead to offer a predictable and standardized execution environment. This execution environment may be provided by the Loosely-coupled Component Infrastructure (LooCI), which runs on Java ME, OSGi and Contiki-based sensor nodes. As sensor nodes cannot be shared, service provision amounts to the leasing of a node which may be implemented using the Policy Based Management Architecture (PMA). In addition to the common execution environment, the infrastructure provider will also include a repository of LooCI components which implement common functionality that may be re-used across multiple applications.

2) *Tangible Platform as a Service (TPaaS)*

While it is infeasible to provide shared, low-level access to sensor network resources, the provision of higher-level software services is quite feasible. For example, the same LooCI component may be shared between multiple concurrent application compositions. Thus, the TSaaS provider may offer a combination of managed infrastructure and generic software components, which a developer may re-use through standard web service technologies. For example, in the warehouse monitoring scenario described in Section II.B.2, the service provider may choose to expose parameterizable tracking and environmental monitoring software components, allowing 3rd parties to compose this data about the tangible world into their application.

3) *Tangible Platform as a Service (TPaaS)*

The integration of sensor network platforms and Cloud Computing provides opportunities to optimize the development process of sensor network applications. The virtualization of hardware platforms offer a consistent development interface for different sensor types and sensor network styles.

The Tangible Platform as a Service interface provides tools and support for developers of Tangible applications in the cloud. The applications are developed, tested and deployed on the same cloud infrastructure as their eventual deployment. For Tangible Cloud applications, this means coordinated and supported development using simulated and actual sensors.

C. *Pricing Models for the Tangible Cloud*

For the Tangible Cloud to be fully accepted and integrated with current infrastructure it must be publicly accessible. The access method for Cloud services (and therefore Tangible Cloud services) is by users purchasing openly available services. As with any complex Information Technology service, purchasing Tangible Cloud services consists of many multifaceted decisions and choices.

Tangible Cloud resources are by nature complex, containing many types of resources, making it difficult to quantify their value. One possibility is to treat each task as a request for a multi-attribute bundle of resources [21]. This is an annotated list of all the required resources needed, their quantities and the required timing. For example, the bundle $B1=N^{nc}T^{t}R^{m}$ describes a bundle of resources in a Tangible Cloud service, n is the number of nodes N required, c being the category type of node, t is the time required and m is the maximum monetary value a resource consumer is willing to pay for the resource R.

Resource providers can then also describe their available resources as bundles of resources, this time specifying the minimal price they are willing to provide resource. To optimally match resource providers and consumers is a well-known resource matching optimization problem [22]. This is done using intermediary brokers who maintain a list of resource requests and offers, matching them if possible.

As with Cloud services such as Amazon EC2 [1], Tangible Cloud services may be made available for purchase for future expected use (reservation) and immediate use (on-demand). This provides maximum flexibility for both resource provider and consumer.

D. *The Architecture of the Tangible Cloud*

Figure 1 provides a comparison between the software stack for traditional Cloud Computing and Tangible Cloud Computing. Figure 1 illustrates how both traditional Cloud Computing and Tangible Cloud Computing use a virtualization layer. In the case of traditional Cloud Computing, this virtualization interface may be provided by Xen [3]. In the case of the Tangible Cloud, standard virtual machines may be required together with custom abstraction logic for the specific hardware platform.

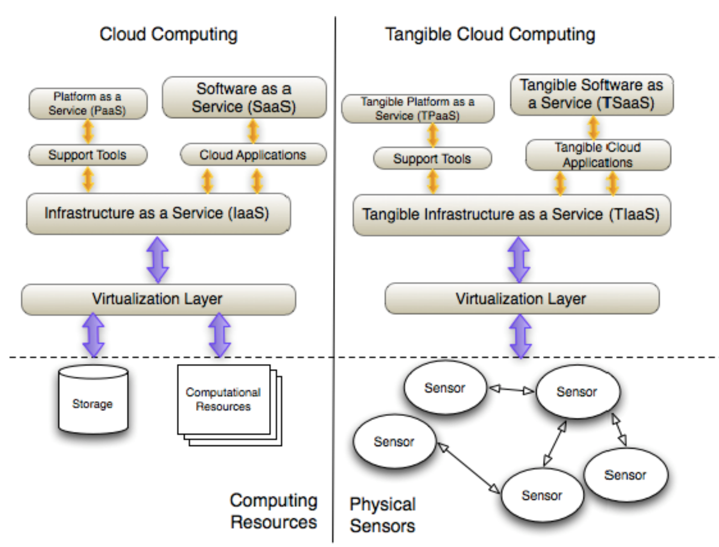

Figure 1: The Architecture of the Tangible Cloud

There are strong comparisons between the Cloud Computing stack and the Tangible Cloud Computing Stack. Both IaaS and TIaaS provide an abstraction of the underlying hardware, allowing almost direct access to the lower-level resources. PaaS and TPaaS provide a development and support environment for application development through the use of support tools on top of the IaaS and TIaaS. Finally, SaaS and TSaaS provide a complete ready to use application based on both computing and sensor resources respectively. As with computing resources in the Cloud, the physical sensors in the Tangible Cloud can be provided by traditional service providers as well as in a give-and-take arrangement with customers as in a hybrid cloud.

IV. Conclusions

This paper has argued for a new direction in sensor network research that strives towards an open, shared infrastructure model, similar to that offered by Cloud Computing. We refer to this vision as the Tangible Cloud. To support this, we have presented a number of motivating scenarios, supporting technologies and an architectural model for the provision of Tangible Cloud services.

The clean separation of concerns offered by the Tangible Cloud allows the various stake-holders involved to focus on their core competencies and thus promises significant gains in efficiency. Furthermore, the virtualization of heterogeneous underlying resources allows for application on a larger scale than is currently possible.

V. Future Work

Our future work will focus on realizing an implementation of the Cloud Computing ecosystem described in Section III.D. This will involve a coherent combination of supporting technologies, high level support for application composition and monitoring and perhaps most critically the development of a public pricing model for Tangible Cloud resources.

References

[1] Amazon Elastic Compute Cloud (EC2), available online: http://aws.amazon.com/ec2/, accessed July 2010.

[2] SliceHost Cloud Services, available online: http://www.slicehost.com/

[3] Barham P., Dragovic B., Fraser K., Hand S., Harris T., Ho A., Neugebauer R., Pratt I., Warfield A., Xen and the Art of Virtualization, in proc. of 19th ACM symposium on Operating Systems Principles, Bolton Landing, NY, USA, October 2003, pp. 164-177.

[4] Google App Engine, available online at: http://code.google.com/appengine/

[5] Sales Force, available online at: http://www.salesforce.com/platform/

[6] A. Dubey, and D. Wagle, "Delivering software as a service," The McKinsey Quarterly, May 2007.

[7] Hughes D., Greenwood P., Coulson G., Blair G., Pappenberger F., Smith P., Beven K., An Experiment with Reflective Middleware to Support Grid-based Flood Monitoring, in Wiley Inter-Science Journal on Concurrency and Computation: Practice and Experience, vol. 20, no 11, November 2007, pp 1303-1316.

[8] Stankovic J. A., Cao Q., Doan T., Fang L., He Z., Kiran R., Lin S., Son S., Stoleru R., Wood A., Wireless Sensor Networks for In-Home Healthcare: Potential and Challenges, in proc. of Workshop on High Confidence Medical Devices Software and Systems (HCMDSS), 2005.

[9] Pohl A., Krumm H., Holland F., Stewing F. J., Lueck I., Service-Orientation and Flexible Service Binding in Distributed Automation and Control Systems, in Proc. of the 22nd International Conference on Advanced Information Networking and Applications – Workshops (IANA), Okinawa, Japan, March 2008, pp. 1393 – 1398.

[10] Vaquero L. M., Rodero-Merino L., Caceres J., Lindner M., A Break in the Clouds: Towards a Cloud Definition, in Computer Communication Review, Vol. 39, No. 1, pp. 50-55, January 2009.

[11] Glombitza N., Pfisterer D., Fischer S., Integrating wireless sensor networks into web service-based business processes, in proc. of 4th International Workshop on Middleware Tools, Services and Run-Time Support for Sensor Networks, Urbana Champaign, Illinois, USA, December 2010, pp. 25-30

[12] Terracotta Cloud Tools, Terracotta Inc, available online: http://www.terracotta.org/start/start-cloud-tools, accessed July 2010.

[13] OpenStack: The open source, open standards cloud, available online: http://openstack.org, accessed July 2010.

[14] B Sotomayor, R S Montero, I M Llorente, Ian Foster, Virtual Infrastructure Management in Private and Hybrid Clouds, IEEE Internet Computing (2009), Volume: 13, Issue: 5, Department, Pages: 14-22, 2009.

[15] Eucalyptus, D. Nurmi et al., "The Eucalyptus Open-Source Cloud-Computing System," Cloud Computing and Applications 2008 (CCA 08), 2008.

[16] Huygens C., Hughes D., Legaisse B., Joosen W., Multi-Paradigm Programming for Wireless Sensor Networks, in IEEE Software, special edition on Multi-Paradigm Programming (to appear).

[17] G. Coulson, G. Blair, P. Grace, F. Taiani, A. Joolia, K. Lee, J. Ueyama, T. Sivaharan, T, A Generic Component Model for Building Systems Software, ACM Transactions on Computer Systems, pp 1-42, Vol. 26, No. 1, February 2008.

[18] LooCI: A Loosely-coupled Component Infrastructure for Networked Embedded Systems, Hughes D., Thoelen K., Horré W., Matthys N., Michiels S., Huygens C., Joosen W., in the proceedings of the 7th International Conference on Advances in Mobile Computing & Multimedia (MoMM'09), December 2009.

[19] Matthys N., Hughes D., Michiels S., Huygens C., Joosen W., Fine Grained Tailoring of Component Behaviour for Networked Embedded Systems, in proc. of the 7th IFIP Workshop on Software Technologies for Future Embedded and Ubiquitous Systems (SEUS'09), Santorini, Greece, November 2009.

[20] Genie: Supporting the Model Driven Development of Reflective, Component-based Adaptive Systems, Bencomo N., Grace P., Flores C., Hughes D., and Blair G., in the proceedings of the 30th International Conference on Software Engineering, ICSE 2008, Leipzig, Germany, May 2008, IEEE.

[21] B. Schnizler, D. Neumann, D. Veit, and C. Weinhardt. Trading grid services - a multi- attribute combinatorial approach. European Journal of Operational Research, 187(3):943– 961, 2008.

[22] G. Buss, K. Lee, D. Veit, Scalable Grid Resource Allocation for Scientific Workflows using Hybrid Metaheurstics, 5th International Conference on Grid and Pervasive Computing (GPC 2010), Hualien, Taiwan, 10-14 May 2010.