UNISENSE: A Unified and Sustainable Sensing and Transport Architecture for Large Scale and Heterogeneous Sensor Networks

Yunye Jin and Hwee Pink Tan

Abstract. In this paper, we propose UNISENSE, a unified and sustainable sensing and transport architecture for large scale and heterogeneous sensor networks. The proposed architecture incorporates seven principal components, namely, application profiling, node architecture, intelligent network design, network management, deep sensing, generalized participatory sensing, and security. We describe the design and implementation for each component. We also present the deployment and performance of the UNISENSE architecture in four practical applications.

1 Introduction

1.1 Background

According to the World Bank, over 52% of the world's population are living in urban areas by the year 2012 [1]. The global trend of increasing urbanization has profound environmental and social impacts. Monitoring environmental status, public infrastructure heath, and commercial service qualify in real time over large scale is critical for urban life quality and sustainable urban development.

1.2 Motivation

Wireless sensor network (WSN) architectures are receiving increasing recognition as a viable approach for urban management. In CommunicAsia 2013, the Infocomm Development Authority of Singapore has revealed the vision of making Singapore 'the first country in the world to be covered by a sensor fabric that connects

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"everything" and collects data to improve the performance of areas such as healthcare, education, utilities and environmental monitoring'[2].

Indeed, various WSN deployments have been proposed for practical applications, such as environmental [3] and infrastructure [4] monitoring. The design and implementation of such deployments are highly specific to the particular application of interest, hence not able to incorporate heterogeneous sensing applications. There are also various Internet of Thing (IoT) testbeds that support multiple sensing modalities at various scales, such as MoteLab ([5]), CitySense ([6]), and SmartSantander ([7]). These testbed infrastructures are restricted to specific commercial hardware modules, which limits extension of application range and evolution of technology.

1.3 Contributions

In this paper, we propose UNISENSE, a unified and sustainable sensing and transport architecture for large scale and heterogeneous sensor networks. Our UNISENSE architecture is distinguished from existing WSN architectures and deployments by the following features and advantages.

1. **Heterogeneity:** In UNISENSE, an application profiling (AP) component automatically matches heterogeneous sensing and networking requirements with a combination of suitable hardware parts. The UNISENSE node architecture (UNA) defines a modular approach to interface these hardware parts flexibly. Moreover, we propose a generalized participatory sensing (gPS) component in order to complement the static sensing architecture.
2. **Scalability:** In UNISENSE, we develop a hierarchical network architecture with automatic network discovery mechanisms and multi-hop multi-sink routing protocols. New sensor nodes, network clusters, and third-party legacy systems can be easily incorporated into our network. Our architecture organizes data streams based on sensor applications rather than plain addresses to improve scalability. Back-end servers are designed to dynamically allocate resources on-demand in order to serve thousands of sensor nodes and back-end applications.
3. **Sustainability:** Through the UNISENSE network management (NM) component, system administrators can monitor and visualize the real-time status of the entire network architecture. Moreover, NM provides capability to remotely control and configure network elements, which facilitates sustainable operation. In addition, the security, trust, and privacy (STP) mechanisms of UNISENSE are customized for large scale sensor networks for the authenticity, integrity, and confidentiality of the sensor data.
4. **Deep sensing:** We translate deep learning techniques into the UNISENSE architecture to improve communications, facilitate data recovery, optimize system deployments, and enhance network management. Deep learning uses only simple neuronal operations, which allows sophisticated data processing to be decentralized from the back-end. This feature enables the network to perform more efficiently with its limited resources, function more intelligently in its operations,

and react more quickly to its environment. It also reduces the risk of a single point of failure.

1.4 Organization of the Paper

The rest of the paper is organized as follows. Section 2 describes the design of each component of the UNISENSE architecture. Section 3 describes four practical UNISENSE deployments, with some reflections on practical lessons learnt. Section 4 points out the comparative advantages of our UNISENSE architecture compared with other existing WSN architectures. Finally, we conclude the paper in Section 5 and describe the ongoing research and development efforts.

2 The UNISENSE Architecture

2.1 Overview

Fig. 1 provides an overview of our UNISENSE architecture. In each application scenario, the AP component characterizes the heterogeneous application requirements and constraints and matches them with an suitable combination of hardware

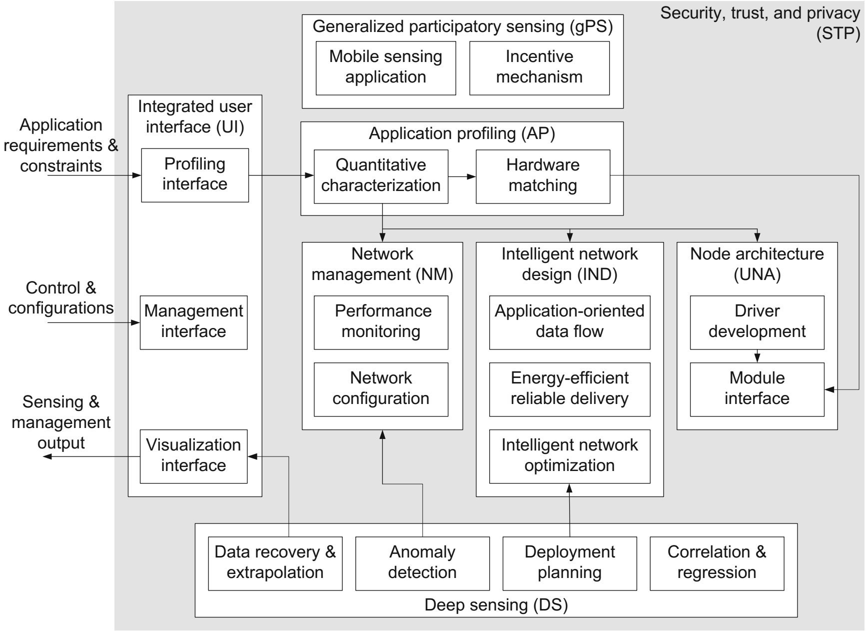


Fig. 1 Overview of the UNISENSE architecture

solutions, which are interfaced by UNA in a modular manner. The IND, NM, and DS components will then optimize the designs and customize the configurations for the specific application requirements and constraints. Clients can get real-time updates of their respective sensing results and control application-specific sensing operations though our UI. The gPS plays an important complementary role to the static WSN infrastructure. The STP component of our architecture ensures each step of the sensing and transportation for each application is secure, trustworthy, and confidential.

2.2 Application Profiling

Application requirements, environmental constraints, and hardware module capabilities are three important aspects concerning the design and deployment of WSNs. In UNISENSE, the AP component quantitatively characterizes these three aspects by specifying the values of an extensive and standard list of parameters in each aspect.

The UNISENSE AP automatically matches a set of specified application requirements and deployment constraints with a suitable set of hardware modules. The matching is performed in an application-oriented manner. Sensor and networking modules are first selected based on sensing and networking requirements. MCU main board is then selected to best interface and power the sensing and networking modules. Lastly, the powering module, including energy harvesters and batteries, are selected based on the overall power consumption of the other selected modules.

2.3 Node Architecture

A UNISENSE sensor node consists of five major components, namely, sensor, actuator, networking, power, and auxiliary. As shown in Fig. 2, the UNISENSE node architecture specifies the standardized interface and schedule mechanism for these components. After AP matches a specific application with the appropriate hardware parts, suitable drivers for each part will be invoked in a modular manner.

The modular nature of our node architecture facilitates collaborative development and technological evolution. Drivers for individual modules can be flexibly

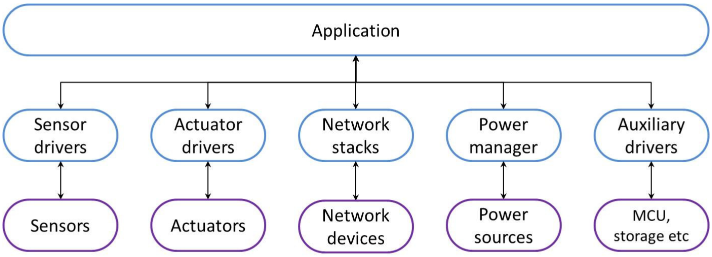


Fig. 2 UNISENSE node architecture model

re-used or modified based on application needs, without affecting other modules' operations. We have also adopted a multi-platform software architecture with the appropriate abstraction models, so that the same software application can be developed for multiple hardware platforms with minimal or no re-development efforts.

We are currently developing an automated device driver invocation system that consistently select software drivers that correspond to the hardware components recommended by AP.

2.4 *Intelligent Network Design*

As shown in Fig. 3, our UNISENSE architecture adopts a hierarchical network organization. Sensor nodes forward their sensor data to the network gateways, which in turn deliver data to the back-end.

Our outdoor sensor network deployments often rely on ambient energy sources, such as solar, which are highly unstable. We have developed an adaptive duty-cycling mechanism that dynamically turns on/off the wireless interface of sensor and gateway nodes in order to achieve energy neutral operation, taking real-time ambient energy availability and networking requirements into consideration.

In order to add sensor nodes to the network architecture in a plug-and-play manner, we have developed an automatic network discovery protocol for newly added sensor nodes to automatically and securely register with nearby gateway nodes and start sensing operations. Moreover, we have also developed a multi-hop multi-sink routing protocol, which enables reliable and fail-safe sensor data delivery.

At the network gateway, we employ a publish-subscribe mechanism, in which gateways "publish" sensor data to the broker (back-end server) and interested users can then "subscribe" to the broker to receive data streams based on topics. This mechanism organizes data based on applications, instead of source-destination address pairs, which facilitates easy integration with third-party legacy systems.

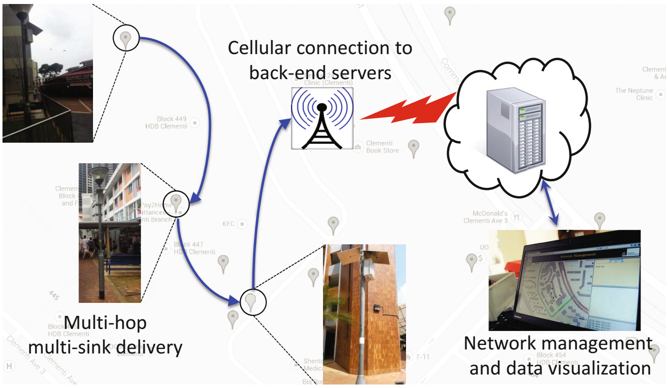


Fig. 3 UNISENSE network architecture

2.5 Network Management and Visualization

In order to ensure sustainable sensing and networking operations of the UNISENSE architecture, the NM component offers a suite of management tools that perform,

1. performance monitoring of sensing, networking, and energy harvesting of the infrastructure at various levels (node, cluster, network) in real time with light weight and low overhead,
2. configuration of the sensing and networking operations and software upgrade of the network infrastructure,
3. mechanisms to track and correlate all changes to the network and its performance for tuning and resource management,
4. alert, diagnosis, and remedy of faults and anomalies,
5. and a unified web-based visualization and control interface for meaningful representation and organization of management information.

2.6 Deep Sensing

The UNISENSE DS component applies state-of-the-art machine learning principles in the design of the WSN architecture by exploiting spatial-temporal correlations in sensor and management data. We employ ideas from a recent advance of neural network technique called *deep learning* [8, 9] to improve the performance and derive actionable insights from the sensor network with limited resources.

By translating deep learning techniques, we have developed the following capabilities for WSN applications.

1. Recovery of missing sensor data due to network loss.
2. Detection of outliers in sensor data as well as anomalies in network operations.
3. Deployment planning in order to fulfill extended coverage requirements with limited hardware resource.
4. Multivariate correlation and regression analysis to assist production and logistic decision makings.

2.7 Generalized Participatory Sensing

The gPS component in UNISENSE exploits sensors on smart mobile devices to complement the static sensing infrastructure.

The major challenges for PS to achieve wide industry adoption are incentive and trustworthiness. In UNISENSE, we have developed an optimized reward scheme that utilizes game theoretics and social networks in order to cultivate a stronger sense of responsibility and accountability among participants and motivate them to contribute higher quality and more trustworthy data.

2.8 *Security, Privacy, and Trust*

The UNISENSE security solution incorporates a suite of light-weight and energy-efficient cryptographic schemes. It also handles multi-user authentication and intrusion detection. Moreover, it provides a strong security feature into the over-the-air (OTA) programming mechanism for NM purposes.

For both the static and the participatory sensing aspects of the UNISENSE architecture, trust management detects and handles attacks on the trusted network infrastructure. Trust management also assures users of the UNISENSE architecture that their data are handled in an safe and honest way.

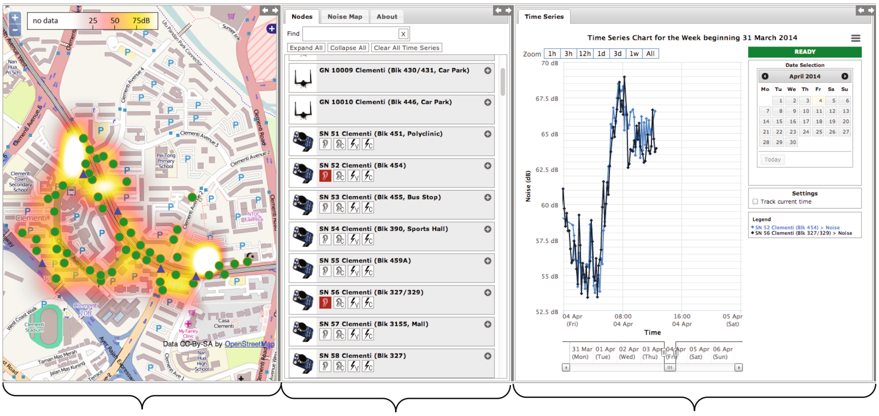
In the UNISENSE architecture, the privacy of the communications is preserved not only at the user end, but also during the transportation in the network by anonymization techniques, improved identity management schemes, and privacy-preserving data analytics and aggregation.

3 Case Studies

3.1 *Urban Noise Monitoring*

Noise monitoring is an important application in urban management. The conventional practice of ad hoc measurement has poor temporal and spatial coverage. Empowered by the UNISENSE architecture, we have developed and deployed a real-time continuous ambient noise mapping system.

Each noise sensor node consists of low-cost noise sensor, processor, networking, and power hardware, interfaced by UNA. An A-weighting noise level computation algorithm is tailored for the resource-constrained sensor node. The multi-hop



Visualization for noise map and nodes

Network management and monitor panel

Time series visualization panel for sensor and network performance data

Fig. 4 Integrated back-end interface for urban noise mapping system multi-sink routing protocol delivers data reliably on top of the adaptively duty-cycled sensor and gateway nodes. Battery level and packet delivery ratio are closely monitored through NM toolkits.

The DS component performs missing data recovery and continuous noise map construction at the back-end in real time. As shown in Fig. 4, we have created an integrated interface that visualizes the continuous noise map and time-series. Node operation status can also be conveniently monitored for network management purposes through the same interface.

By Mar. 2014, we have successfully deployed two noise mapping testbeds in two typical urban sites in Singapore, namely, Clementi Town Central and Jurong Lake District. Each testbed consists of 50 solar-powered noise sensor nodes and 4 solar-powered gateway nodes installed on the lamp posts. Every five minutes, each sensor node measures and updates noise level, in dBA, to the back-end server, which in turn updates the time-series and spatial heat map visualizations.

3.2 Public Infrastructure Monitoring (Smart Bins)

Currently, most rubbish bin cleaning service are conducted in a routine manner. Resources are often wasted on clearing some half-filled rubbish bins, while having other overflowing. The Smart Bins deployment aims to solve this problem by providing a real-time update of the bin fullness level, allowing operators to deploy resources in an adaptive manner rather than a routine manner.

Leveraging on the UNISENSE architecture, Smartbins utilizes ultrasonic sensors to sense the fullness level of the bin, and update the back-end through the hierarchical network infrastructure. We also use GPS and accelerometer modules to monitor the location of the bins as they are susceptible to movements by the public, as well as provide accurate timestamps for data. Fig. 5 shows a sensor node for smart bins.

By Apr. 2014, we have deployed 11 sensors, 4 multi-hop and 7 single-hop, over Geylang Road and Guillemard Road in Singapore. With an update interval of five

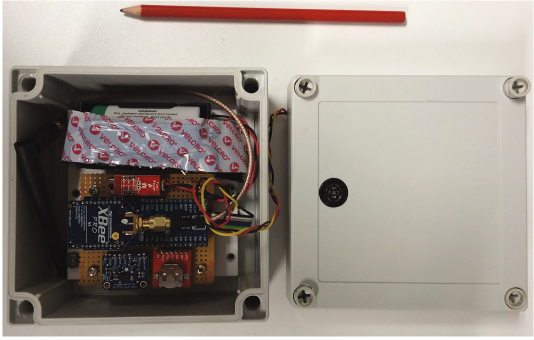


Fig. 5 A Smart Bins sensor node

minutes and a 13 Ah non-rechargeable battery, none of the sensors have required battery replacements since our deployment commenced in Dec. 2013. We are able to achieve more than 90% packet delivery ratio for all the 4 bins with multi-hop routing scheme.

3.3 Event Management (CuteBit)

3.3.1 Application Scenario

CuteBit is a real-time event participation system empowered by the UNISENSE architecture. It provides an intuitive button-less UI to support voting, ranking, and participatory games by simply flipping the CuteBit to different faces.

Each CuteBit is a battery-powered MCU main board equipped with an accelerometer and a 802.15.4 wireless module. The user inputs are captured by sensing the orientation of the CuteBit. A multi-sink routing protocol delivers user input reliably to the gateway nodes in real time.

On 8 May 2013, 42 CuteBits were deployed for a dinner event. One CuteBit sensor node was placed on each dinner table for participation input from this table. The CuteBit system performed three tasks during the event successfully, namely, collaborative event launch, voting, and crowd activity level monitoring. Fig. 6 is a screenshot of the voting visualization.

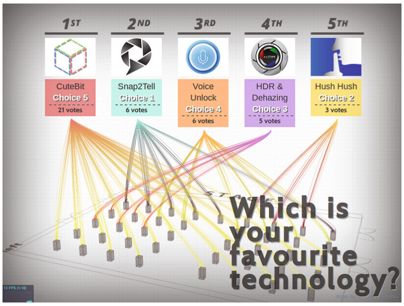


Fig. 6 Voting visualization interface for CuteBit

3.4 Vertical Farming Monitoring

Monitoring vertical farming is a new application domain for WSNs. By deploying WSN on vertical farm towers, we aim to, (i) increase the crop yield through in-depth sense-making of the sensor data and crop growth bio-data, and (ii) improve productivity through reduced reliance on manual monitoring.

We deployed a total of 115 solar powered sensor nodes on a vertical farm to measure multiple environmental parameters including ambient light, temperature, and humidity. The sensors were deployed on 115 rotating towers inside greenhouses for a period of 30 days. All sensor nodes are adaptively duty-cycled to achieve energy neutral operation using solar power. As a result, all sensor nodes have achieved 100% uptime over the 30 days deployment. The DS component performed correlation and regression analytics on the multi-modal sensor data with crop growth bio-data. Fig. 7 show the multi-modal sensing node.

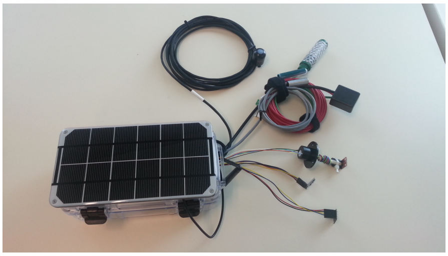


Fig. 7 Multi-modal sensor node for farm use

3.5 Practical Issues and Lessons Learnt

The design, implementation, and deployment of the four testbeds have provided us valuable experience for practical WSN realizations. We summarize them as follows.

1. In practical environments, many dynamic factors, such as weather conditions and traffic flows, significantly affect the operating conditions of the WSN deployment. Therefore, it is advisable to always over-provision for energy harvesting capabilities and wireless antenna gains in order to ensure network uptime and connectivity, respectively.
2. Operating condition in many deployment environment can be hostile to the node hardware. Weatherproof and insulation efforts are the keys to protect sensor node hardware from corrosion or short circuit. Programs and scripts running in sensor and gateway nodes should always be designed with fail-safe and auto-recovery features.
3. At both the node and the network level, our architecture design adopts a modular approach. This not only enables future re-use of both hardware and software modules, but also makes development collaboration, debugging, and upgrading much easier. In the setup and maintenance of our deployments, we have taken full advantage of the modular design of the nodes, replacing and upgrading the parts in a plug-and-play manner.

4 Related Work and Competitive Advantages

Various WSN deployments have been utilized for practical applications. In [3], a WSN was deployed to monitor volcano activities. In [4], a WSN was deployed to manage a combined sewage overflow control system. In these cases, the network planning and the hardware choice are highly specific and fixed to the particular application requirements. Such an application-specific approach cannot support the coexistence of heterogeneous sensing applications in a cost-effective manner. In contrast, our UNISENSE architecture utilizes the AP component to quantitatively characterize the application requirements and constraints, while UNA allows the most suitable hardware modules for each application to be flexibly interfaced together.

Various WSN and Internet of Thing (IoT) testbeds can support multiple sensing modalities and applications. For example, MoteLab [5] is an indoor WSN testbed, with dedicated energy measurement, reprogramming, and management interfaces. CitySense [6] is an outdoor urban WSN testbed consisting of embedded Linux PCs with weather and air quality sensors. The SmartSantander [7] testbed consists of $20,000$ heterogeneous IoT sensors and devices. Although featured with multiple sensing modalities and reprogrammability, these testbeds are restricted by specific commercial hardware modules, which limits the long term technical evolution. Moreover, such testbeds usually incorporate a dedicated management and evaluation sub-infrastructure, which incurs high hardware cost. In contrast, the UNISENSE NM component manages the network infrastructure in an in-network manner with minimum extra hardware and overhead.

To the best of our knowledge, the UNISENSE architecture is the first to have a dedicated machine learning component (DS). The learning capability enables outlier and anomaly detection, missing data recovery, and mining for actionable insights, which brings our infrastructure closer to real world applications.

5 Conclusion and Ongoing Work

In this paper, we have introduced the UNISENSE architecture for large scale heterogeneous WSNs, as a technology enabler for smart cities realization and management. We described the design approach and implementation progress for each principal component of the architecture. We have also presented the deployment and performance of four practical WSNs supported by our architecture.

We point out future work in the following aspects. The UNA will be expanded to support more hardware platforms and interface types in our architecture. Besides the existing automatic hardware matching capability, we aim to automate the choice of driver software in the AP component. For network planning, an IND toolkit will be designed to intelligently determine network topologies, select suitable protocols, and configure the optimal operating parameters.

A suite of scalable NM methods for configuration changes logging, performance tracking, and higher-order fault detection will be developed. An integrated security, trust, and privacy solution suite will be developed for resource-constrained WSN nodes. Deep learning techniques will be translated to facilitate distributed processing, simplified network codec, response time improvement, and data compression. For gPS, we will focus on the design and enhancement of incentive schemes as well as user data quality evaluation mechanism.

References

1. The World Bank, Data on Urban Population (July 2013), `http://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS/countries/1W?display=graph`
2. CommunicAsia 2013 The Official Daily News, IDA Envisions Sensor Fabric for Singapore (June 2013), `http://www.communicasia.com/post-show/downloads/CMMA2013_showdaily03.pdf`
3. Werner-Allen, G., Lorincz, K., Ruiz, M., Marcillo, O., Johnson, J., Lees, J., Welsh, M.: Deploying A Wireless Sensor Network on An Active Volcano. IEEE Internet Computing 10(2), 18–25 (2006)
4. Montestruque, L., Lemmon, M.: CSOnet: A Metropolitan Scale Wireless Sensor-Actuator Network. In: Proc. International Workshop Mobile Device and Urban Sensing (2008)
5. Werner-Allen, G., Swieskowski, P., Welsh, M.: MoteLab: A Wireless Sensor Network Testbed. In: Proc. IEEE IPSN, pp. 483–488 (2005)
6. Murty, R.N., Mainland, G., Rose, I., Chowdhury, A.R., Gosain, A., Bers, J., Welsh, M.: CitySense: An Urban-Scale Wireless Sensor Network and Testbed. In: Proc. IEEE Conference on Technologies for Homeland Security, pp. 583–588 (May 2008)
7. Gluhak, A., Krco, S., Nati, M., Pfisterer, D., Mitton, N., Razafindralambo, T.: A Survey on Facilities for Experimental Internet of Things Research. IEEE Communications Magazine 49(11), 58–67 (2011)
8. Hinton, G.E., Salakhutdinov, R.R.: Reducing the Dimensionality of Data with Neural Networks. Science 313(5786), 504–507 (2006)
9. Lee, H., Grosse, R., Ranganath, R., Ng, A.Y.: Convolutional Deep Belief Networks for Scalable Unsupervised Learning of Hierarchical Representations. In: Proc. Annual International Conference on Machine Learning, pp. 609–616. ACM (2009)