Quintessence of Existing Testbeds for Wireless Sensor Networks

Rahul Kumar Chawda[1], A.K. Dwivedi[2]

School of Information Technology
MATS University
Raipur (C.G.) 492001, India

***Abstract*— Research activities in the area of WSNs need expositive performance statistics about scenario, systems, protocols, gathered data and applications. The objective of this contribution is to present an epitome on currently available testbeds for wireless sensor networks. The statistics gathered from this experimental tool can be realistic and convenient, and also due to cost of large number of sensors most researches in WSNs area is performed by using this experimental tool in various universities, institutes, and research centers before implementing real one. This experimental tool provides the better option for studying the behavior of WSNs before implementing the physical one. In this contribution total 51 testbeds has been presented in which 35 testbeds are presented in useful decisive manner with respect to WSN while rests are just listed; these experimental tools are implemented in somewhere for WSNs research or available in literatures.**

***Index Terms*— Wireless Sensor Networks, Testbeds, Experimental Tools.**

I. Introduction

Wireless Sensor Networks (WSNs) have recently emerged as a premier research topic and gaining huge attraction by researchers due to its wide suitability for military applications, environmental applications, health applications, domestic and other commercial applications. There are some factors that really influencing WSNs design: production cost, hardware constrains, energy consumption, environment, transmission media, network topology, fault tolerance, scalability etc. The primary goal of testbeds for WSNs is to offer an accurate and efficient scientific tool to help in the design, development, tuning, and experimentation of real large-scale sensor network applications. Like simulators for WSNs, testbeds are designed and implemented for specific goals, like evaluating multiple localization algorithms, network security algorithms etc. As per experimental requirements testbeds for WSNs can have indoor or outdoor setup. Real outdoor WSNs testbed will face challenges not seen in indoor environment, including remote over-the-air-programming, unattended nature and efficient energy use.

Testbeds for WSNs are critical for understanding and meeting the technical challenges of networks deployed in real world application scenarios. Testbeds provide a means for developing and evaluating sensor network technology in a fully controlled and instrumented environment. Experimentation in research labs with hardware and software platforms, allows users to not only demonstrate applicability in real world environments but also to validate prototypes. Compared to field deployments, the testbeds yield substantial efficiency in instrumenting potentially long-lived experiments, which is valuable in the debugging, validation, and integration phases of reliable WSNs. Universities, Institutions, Private and Public research labs, and industries across the world have set up networks of hundreds of nodes using MICA, TelosB, Imote etc. Each testbed across the world utilizes a specific sensor node that is optimized for that particular testbed's objectives. Testbeds allow the observation of the performance of WSNs in a fully monitored and controlled environment. Hence, the effect of different types of inputs, physical operating conditions, and subjects for sensing can be studied, and the functioning of the devices in the testbed may be changed appropriately for accurate measurement.

In general, testbeds allow for rigorous, transparent and replicable testing. Obstacles to use testbeds are:

- Due to limited research fund budgets at research institutes and universities it is very expensive to maintain a testbed with large number of sensor nodes.
- For hazardous applications (e.g., forest fires detection, flood detection, erupting volcano monitoring, detecting chemical/ biological/ radiological/ nuclear/ explosive material) deploying a real testbed can cause serious damage of sensor nodes and testbeds.
- By providing the realistic environments for testing the experiments, the testbeds bridge the gap between the simulation and deployment of real devices. The testbeds thus deployed can improve the speed of innovation and productive research.

II. Problem Formation

As discussed in introduction section every testbed across the world utilizes specific selected sensor node platforms that are optimized for that particular testbed's objectives. But due to highly optimized nature of its sensor nodes, it is not possible to have one solution for all [14] the different kind of applications. For carrying out research and development in WSNs, it is important to have access to a wireless sensor network testbed, which is flexible to suit the requirements of different applications and technological developments.

A lot of good quality research contributions present comparative study of some simulators and testbeds, a research contribution [28] presents comparison of different testbeds on physical and design parameters but this is just a little bit of an emerged broad area. Also there is no any single research paper that present a detail survey or review study on testbeds available for WSNs research work. The objective of this contribution is to present an extensive survey on testbeds especially used for WSNs research purpose. In next section total 51 testbeds has been presented in which 35 testbeds are presented with highly summarized pros and cons features with respect to WSNs research while rest are just listed.

III. Testbeds for Wireless Sensor Networks

Testbeds for WSNs are an environment that provides support to measure number of physical parameters under reliable and controlled experimental environment. This investigational environment contains the physical hardware devices, instrumentations, simulators, software tools and other support elements needed to accomplish an experiment. To achieve high-fidelity in WSN experiments use of testbed is very productive and useful.

By providing the realistic environments for testing the experiments, the testbeds bridge the gap between the simulation and deployment of real devices. The testbeds thus deployed can improve the speed of innovation and productive research. Besides saving the deployment effort, a testbed, due to limited sensors and controlled setting, allows for a certain predictability of the experimental environment.

In this section 35 testbeds are presented in summarized way, used for experimental purposes in various universities, colleges, research institutions or by individuals.

3.1. Motelab [1]

An experimental WSN deployed in Maxwell Dworkin Laboratory, the Electrical Engineering and Computer Science building at Harvard University. It consists of a set of permanently-deployed sensor nodes connected to a central server which handles reprogramming and data logging while providing a web interface for creating and scheduling jobs on the testbed. It accelerates application deployment by streamlining access to a large, fixed network of real sensor network devices, also accelerates debugging and development by automating data logging, as well as allowing the performance of sensor network software to be evaluated offline. Additionally, by providing a web interface it allows both local and remote users to access the testbed, and ensuring fair sharing by using scheduling and quota system. Its source is freely available, easy to install, thus widely used.

3.2. Tutornet: A Tiered Wireless Sensor Network Testbed [2]

Tutornet consist of 13 clusters, with each cluster consisting of a stargate and several motes attached via USB cables. Thus a testbed consisting of 13 stargates and 104 motes (91 tmoteSky and 13 MicaZ). These stargates communicate with a central PC over IEEE 802.11b, from where nodes on the testbed can be programmed. It consists of 3 tiers and provide remote and parallel programming mote.

3.2. WUSTL [3]

This testbed is deployed at Washington University and currently consists of 79 wireless sensor nodes (motes). Testbed deployment is based on the TWIST architecture originally developed by the telecommunications group (TKN) at the Technical University of Berlin. It is hierarchical in nature, consisting of three different levels of deployment: sensor nodes, microservers, and a desktop class host/server machine.

3.4. CitySense [4]

CitySense is an urban scale sensor network testbed that is being developed by researchers at Harvard University and BBN Technologies. Consists of 100 wireless sensor nodes mounted to telephone poles that will cover the city of Cambridge, MA, and allow researchers to see the specific locations and times of day when pollution peaks. Each node will consist of an embedded PC, 802.11a/b/g interface, and various sensors for monitoring weather conditions and air pollutants. CitySense is intended to be an open testbed that researchers from all over the world can use to evaluate wireless networking and sensor network applications in a large-scale urban setting.

3.5. Kansei [5]

It is a large-scale testbed including both 210 specially designed Extreme Scale Motes (XSM) and Extreme Scale Stargates (XSS), deployed at the Ohio State University. The topology is using both Ethernet and 802.11b wireless LAN to control the testbed. Kansei also provide a web interface for users to upload programs, scheduled jobs, and retrieve results with EmStar software framework.

3.6. MISTLAB [6]

MistLab consists of a mixture of 47 mica2 nodes and 14 Cricket nodes spread across multiple rooms located on the 9th floor of MIT’s CS department.

3.7. Orbitlab [7]

ORBIT is short for Open-Access Research Testbed for Next-Generation Wireless Networks (including WSN also). It supports experimental research on a broad range of wireless networking issues and application concepts with various network topologies and network layer protocol options. It also supports virtual mobility for mobile network protocol and application research.

3.8. Emulab [8]

Emulab is a network emulation testbed, giving researchers a wide range of experimental environments in which to develop, debug, and evaluate their systems. In addition to fixed wireless nodes (currently predominantly 802.11), Emulab also features wireless nodes attached to robots that can move around a small area. These robots consist of a small body with an Intel Stargate that hosts a mote with a wireless network interface. The goal of this "mobile wireless testbed" is to give users an opportunity to conduct experiments with wireless nodes that are truly mobile. TrueMobile and Mobile Emulab are some modified versions for dynamic WSNs.

3.9. WISEBED (Wireless Sensor Network Testbeds) [9]

It provides a multi-level infrastructure of interconnected testbeds of large-scale wireless sensor networks for research purposes, pursuing an interdisciplinary approach that integrates the aspects of hardware, software, algorithms, and data.

3.10. REALnet [10]

REALnet is an embryonic environmental WSN at the UPC (Universitat Politècnica de Catalunya). The technical objective of REALnet is to monitor physical parameters from the air (atmospheric temperature, humidity and pressure, and ambient light), ground (humidity, temperature) and water (level, temperature, conductivity).

3.11. KonTest [11]

KonTest is a 60-node indoor WSN testbed, distributed among six office rooms located on the fourth floor of the Faculty of Sciences of Vrije Universiteit Amsterdam. The testbed includes 60 TelosB-class nodes.

3.12. SANDbed (Sensor Actuator Network Development Testbed) [12]

It is an integrated testbed system for WSN monitoring and management, consists of 3 levels of hardware components organized in a hierarchical tree. The root level comprises the user interface, where the management of the testbed and configuration of the experiments is taking place. Management nodes connected to the Internet form the second level. They are responsible for managing the testbed nodes and controlling the execution of experiments. The leaves of the tree are the testbed nodes, consisting of a mote and the SNMD.

3.13. BANAID [13]

It consists of 07 Mica2 motes and 02 Stargate sensor devices. BANAID is the first actual testbed that shows the visibility of the Wormhole attack in WSN and mainly used to simulate the wormhole attack on a WSN.

3.14. CENSE (A Century of Sensor nodes) [14]

Providing flexible modular platform for testing and optimization of nodes for Sensor Network applications. Each node of the testbed consists of four modules: Power, Processor, Sensor and Communication, but the design can be easily extended to add more modules like mobility and localization. It is very flexible, cost efficient, easy to use, power efficient, provides excellent debugging facilities and covers all major requirements of sensors networks.

3.15. WINTeR (Wireless Industrial Sensor Network Testbed for Radio-Harsh Environments) [15]

It is an open access, multi-user experimental facility (MXF) that supports the development and evaluation of WSNs for radio-harsh environments (RHEs). The testbed supports the R&D of emerging WSN technologies, including protocols, security, physical layer, the validation of wireless solutions for industrial processes, propagation models, and cross-layer optimization.

3.16. NESC-Testbed [16]

NESC-Testbed 1.0 provides an actual platform for the testing and developing of algorithm, protocol in WSN. B/S 3-tier and wireless-wired combined framework are used in this testbed, which makes the system user-friendly, easily used, robust and stable.

3.17. SWOON (Secure Wireless Overlay Observation Network) [17]

SWOON testbed is an emulation-based testbed for real world experiences and scalable tests over an overlay network, consisting of wireless sensor networks, 802.11 a/b/g, etc. It can evaluate protocols, mechanisms and techniques for secure wireless communication. Researchers and designers can create their own topologies and run experiments on the SWOON testbed without re-establishing and re-installing hardware and software modules required for their wireless networks. In addition, the SWOON testbed also allows researchers to monitor the network traffic, evaluate the performance of the protocols under test and validate the researches they presented.

3.18. INDRIYA [18]

INDRIYA is a large-scale 3D WSN testbed with 140 TelosB nodes deployed at the National University of Singapore. The Testbed facilitates research in sensor network programming environments, communication protocols, system design, and applications. It provides a public, permanent framework for development and testing of sensor network protocols and applications. Users can interact with the Testbed through an intuitive web-based interface designed based on Harvard's Motelab's interface.

3.19. CLARITY [19]

CLARITY Centre for Sensor Web Technology in Ireland is currently constructing a ubiquitous robotics testbed by integrating a collective of mobile robots with a WSN and a number of portable devices. The new, mixed testbed will be hosted at University College Dublin, (UCD), and will also avail itself of the laboratory facilities hosted in Dublin City University (DCU) and Tyndall, Cork. This testbed integrates and extends some pre-existing facilities, specifically: WSN of 70 Berkeley motes measuring humidity, light and temperature, 10 mobile robots, equipped with an array of state-of-the-art sensors, including USB cameras, laser range finders, sonar, infrared, odometers and bumpers. Each robot carries a mote able to measure ambient variables, which is also equipped with triple-axis accelerometers, magnetometer, compass and microphone, a variable number of Internet gateways, a variable number of PDAs and mobile phones equipped with Bluetooth.

3.20. Imote2 Sensor Network Testbed [20]

In its current version, the testbed consists of a set of Crossbow Imote2 nodes programmed with a Linux kernel and running localization and routing codes written in C. One node is connected to a PC via USB and acts as a base node for the network. The PC runs a Java-based GUI intended as an interface for a user to read data from the nodes and to issue commands to the network. The user can control and observe the performance of various localization protocols in the network which are run locally in the Linux operating system on each device.

3.21. WSNTB [21]

WSNTB is designed for heterogeneous WSN experiments. It involves two WSNs and three gateways. Each WSN has 17 sensor nodes. According to users' requirements, users can choose the single one or both of WSNs, with or without the gateways to experiment. Users can use both the web-based interface and the special function, called local mode, to run their applications on testbed.

3.22. TWIST [22]

TWIST testbed is hold by Technical University Berlin. They help users load programs and run experiments such as time synchronization and power control. The system is divided into two major parts. The first part is the server to serve the demands of users and control all of nodes. The second part includes two types of sensor nodes, eyesIFX v2 and Telos motes which are plugged onto the switch. The architecture is extended form the UC Berkeley's Omega testbed and Motescope testbed.

3.23. ENL Sensor Network Testbed [23]

The ENL testbed is intended to provide a multi-hop sensor network that could be used for the real time analysis and evaluation of sensor network application. The ENL sensor network testbed consist of a number of mote assemblies hanging from the ceiling forming a grid pattern. Each mote assembly consists of a mica mote and the standard programming board. The testbed provides means of remotely programming the motes and collecting data from the testbed.

3.24. X-sensor [24]

X-sensor a new sensor network testbed integrates multiple sensor networks deployed at different sites. X-sensor provides three functionalities: (a) a sensor network search which enables users to find a sensor networks appropriate for experiment and data acquisition, (b) a sensor data archive which provides users with various sensor data acquired by sensor nodes, and (c) an experimental testbed which enables remote users to evaluate their network and data management protocols.

3.25. GNOMES [25]

GNOMES is a lowcost hardware and software testbed. This testbed was designed to explore the properties of heterogeneous wireless sensor networks, to test theory in sensor networks architecture, and be deployed in practical application environments.

3.26. PICSENSE [26]

The PICSENSE is a single hop WSN testbed which will send the sensor information to the gateway node. The gateway node will act as an embedded web server which serves the web pages with the dynamic data. Most of the testbed uses commercial gateway nodes like stargate which is not as flexible as the Rabbit gateway node, which is used in this testbed to integrate the WSNs with the IP networks. The firmware in the Rabbit gateway node can be designed to make the configuration of the gateway node either as a HTTP server or a FTP server or a simple router.

3.27. SOWNet [27]

The SOWNet Technologies T301 Testbed is primarily a WSN testbed consisting of SOWNet G-Node G301 wireless sensor nodes. Each sensor node is attached to a G-Node testbed adaptor module for connecting the sensor emulation feature. Up to 4 G-Nodes and GTA301 modules can be interfaced to a single mini PC. The mini PC is connected to an IP network using its wired or wireless networking capability. This allows many mini PCs and a vast number of G-Nodes to form a WSN testbed together and still be managed from a single management console, possibly over the internet.

3.28. NetEye [28]

NetEye is a high-fidelity testbed consists of 130 TelosB motes at Wayne State University. In addition to providing a local facility for supporting research and educational activities, NetEye is being connected to Kansei as a part of the Kansei consortium. NetEye testbed consists of a controlled indoor environment with a set of sensor nodes and wireless nodes deployed permanently. NetEye testbed provides a web interface to create and schedule a job on the testbed while automated reprogramming of the sensor devices and storing the experimental data on to the server.

3.29. Casino Lab WSN Testbed [29]

The Casino Lab WSN testbed at the Colorado School of Mines consists of 52 Tmote Sky nodes, hung from the ceiling of a large open industrial space with concrete walls, pipes, ducts and fluorescent lighting. The dimensions of the room is 24.4m×12.30m, and the nodes are deployed in a 4×13 irregular grid. The nodes are connected via USB to 26 Tmote Connect Ethernet bridges providing a wired out-of-band channel for control. The testbed is not publicly available.

3.30. DES-MESH [30]

It is a hybrid wireless mesh and sensor network testbed being developed at the Freie Universität Berlin. It currently consists of 35 hybrid nodes installed in an office setting spanning three floors. The testbed architecture is organized in three tiers: backbone mesh routers, mesh clients and sensor nodes. The mesh routers are equipped with 500 MHz AMD Geode LX800 CPUs with 256 MB of RAM, and have three IEEE 802.11 cards attached via USB hubs. The sensor nodes have 60 MHz ARM 7 cores and Chipcon CC1100 transceivers in the 868 MHz band. The testbed management is realized by a combination of SSH-supported remote command execution and SNMP services. The experiment configuration and control is facilitated by a domain specific language called DES-CRIPT based on XML.

3.31. Deployment Support Network (DSN) Testbed [31]

The DSN is a testbed framework developed at ETH Zürich, which leverages a secondary multi-hop WSN optimized for connectivity and reliability as a testbed backbone. The DSN-nodes forming this backbone network are in turn connected to the SUT nodes via custom wired interfaces. Currently supported SUT node platforms include the BTnode, TinyNode, Tmote Sky and A80. The testbed backbone is used for SUT image file distribution, for transfer of logging and debug data, and for sending direct commands to the SUT nodes. The operation of the testbed is controlled by a DSN-server that exports the DSN-services via XML-RPC and web based interfaces towards the testbed user. The instance of the DSN framework at ETH Zürich uses the BTnode platform and its Bluetooth radio for the backbone network. The current configuration of the testbed consists of 30 backbone nodes and 30 Tmote Sky and TinyNode SUT nodes.

3.32. Illinois Wireless Wind Tunnel (iWWT)[32]

The iWWT is a reduced-scale testing environment for wireless networks implemented in an electromagnetic anechoic chamber at the University of Illinois at Urbana-Champaign. The main aim of the testbed is to create a realistic scaled version of the wireless environment maintaining full control over all relevant parameters that affect the performance of the wireless network like obstructions, interferers, etc. Mobility is supported by placing the wireless hosts (laptops, PDAs, sensor nodes) on top of remotely controlled cars. The scaled wireless environment is constructed by combining the effects of several building blocks: Power control module, Multipath module, Doppler module and Scattering Module. Despite these efforts for complete control of the RF environment, repeatability of small-scale experimental results remains elusive due to intrinsic randomness in the evaluated protocols and object positioning errors.

3.33. Motescope Testbed [33]

The Mote scope testbed at the University of California, Berkeley is an update of the sMote testbed installed in the Soda Hall. The original 78 Mica2Dot nodes in sMote have been replaced with MicaZ nodes in Motescope. The testbed provides convenient web interface for configuration and control of the experiments. The testbed has open access policy for the members of the academic research community.

3.34. WASAL Testbed [34]

The WASAL testbed at the École Polytechnique Fédérale de Lausanne consists of 25 TinyNode nodes connected to a wired testbed back-channel via custom serial-to-ethernet devices that act as passive communication bridges and range extenders. The WASAdmin management tool uses an XML-based configuration language and concurrently executes a separate shell instance and script parser for each target node in the SUT.

3.35. Omega [35]

The Omega testbed at the University of California, Berkeley consists of 28 TelosB nodes, connected via daisy-chained USB hubs to the central control server. This wired back-channel is used for powering, programming and debugging of the SUT nodes. The testbed has open access policy for the members of the academic research community.

In addition to above discussed WSN testbeds, there are also a number of other academic and industrial testbed deployments. Some of these WSN testbeds are: SenseNet [36], Sharesense [37], Trio [38], sMote [39], CTI-WSN Testbed [40], FEEIT WSN Testbed [41], Roulette [42], BigNet [43], UCR Wireless Networking Research Testbed [44], IP-WSN [45], WHYNET [46], CENS-Testbed [47], SCADDS WSN Testbeds [48], GaTech Testbed [49], Intel Research Berkeley's 150-mote SensorNet Testbed [50], VigiNet Testbed [51].

Here is a list presenting 30 testbeds used for experimental purposes in various universities, colleges, research institutions or by individuals:

Table 1: Comparison Table of Some Different Testbeds.

S.N.	Testbed	S/W	Motes	No. of Motes	Participant(s)
1.	Motelab	TinyOS	TMote Sky	190	Harvard University
2.	Tutornet	TinyOS	Tmote Sky, Micaz	91, 13	University of Lubeck, F U Berlin, CTI
3.	WUSTL	PostgreSQL with db	Tmote sky	79	Washington University, Technical University of Berlin
4.	Citysense	FreeBSD 7	Tmote Sky	100	Harvard University
5.	Kansei	TinyOS	XSM and Stargates, Tmote Sky, Trio	210, 150, 50	Ohio State University
6.	MISTLab	TinyOS	Micaz, Cricket	47, 14	MIT's CS Department
7.	BigNet	TinyOS	Sun Spot, Crossbow	75, 210	James Cook University, Deakin University
8.	Emulab	TinyOS	Garcia, Mica2	06, 25	University of Utah
9.	WISEBED	TriSOS	Tmote Sky	750	University of Lubeck (UZL)
10.	KonTest	TinyOS 2.0	TelosB	60	Vrije University Amsterdam
11.	BANAID	TinyOS	Mica2 and Stargate	9	King Abdulaziz City for Science and Technology (KACST)
12.	WINTer	TinyOS	COTS mote	30	Tailored for Radio Harish Environments (RHE) in the Oil and Gas Industry
13.	NESC-testbed	TinyOS	TelosB	140	University of Catania
14.	SWOON	TinyOS, Emulab	DETER Nodes	02	National Chiao-Tung University, Taiwan
15.	INDRIYA	TinyOS, NesC, TOSSIM	TelosB	139	National University of Singapore
16.	Nestbed	TinyOS	Tmote Sky	80	Western Carolina University and Clemson University
17.	WSNTB	TinyOS and LOS	Octopus I and Octopus II	34	National Tsing Hua University, National Central University
18.	Twist	TWISTv1 Software Release, Cooja - TWIST Plugin	Tmote Sky, eyesIFX	102, 102	Technical University Berlin
19.	ENL	TinyOS	Tmote Sky	91	-
20.	NetEye	TinyOS 1.1 TinyOS 2.0.2	TelosB	130	Wayne State University
21.	Casino Lab WSN	TOSSIM	Tmote Sky	52	Colorado School of Mines
22.	DESH-MESH	TinyOS	Hybrid	35	Freie University Berlin
23.	DSN	TinyOS	Tmote Sky, Backbone	60	ETH Zurich
24	Motescope	TinyOS	Mica2Dot	78	University of California Berlin
25	WASAL	TinyOS	Tiny Node	25	E'cole Polytechnique federate de Lausanne
26.	Omega	TinyOS 2.0.2	TelosB	28	University of California Berkeley
27.	SensorNet	TinyOS	MicaZ	150	Intel Berkeley Research Labs
28.	Trio	TinyOS	TelosB	57	University of California Berkeley's
29.	FireSenseTB	TinyOS	Tmote Sky	44	Yeditepe University in Turkey
30.	VigiNet	TinyOS	Mica2	70	Adaptable surveillance strategy achieves a significant extension of network lifetime

IV. EDUCTS OF THIS EPITOMIC STUDY

Designing and validating algorithms and protocols pertaining to wireless sensor networks (WSNs) are among the most fundamental focuses of researchers in this area. Simulation tools are widely used for the purpose of exploratory analysis in these tasks due to their rapid prototyping and tackling large scale systems. However, even the best simulator is still not able to simulate real wireless communication environments in terms of completeness, complexity, accuracy and authenticity. Researchers use emulators of WSNs to selectively track whether their applications have executed as intended. These emulators simulate the hardware environments to facilitate the development and checking software applications. The emulator approach is quite laborious since extensive prior profiling is required. Taking these drawbacks of simulators and emulators into account, using wireless sensor network testbed to evaluate algorithms and protocols of WSNs is essentially necessary before applying them into real world applications. The objective of this study has clearly brought forth important findings that are very useful in wireless sensor network's experiments. To these ends, we believe we have succeeded.

REFERENCES

[1] G. Werner-Allen, P. Swieskowski, and M. Welsh, "MoteLab: A Wireless Sensor Network Testbed," in Proc. 4th International Symposium on Information Processing in Sensor Networks, article 68, April 2005, ISBN: 0-7803-9202-7.

[2] Tutornet Testbed: http://enl.usc.edu/projects/tutornet/index.html

[3] WUSTL Wireless Sensor Network Testbed: http://www.cs.wustl.edu/wsn/index.php?title=Testbed

[4] R. Murty, G. Mainland, I. Rose, A. R.Chowdhury, A. Gosain, J. Bers, and M. Welsh, "CitySense: A Vision for an Urban-Scale Wireless Networking Testbed," in Proc. IEEE International Conference on Technologies for Homeland Security, Waltham, MA, May 2008. doi:10.1109/THS.2008.4534518

[5] E. Ertin, A. Arora, R. Ramnath, M. Nesterenko, V. Naik, S. Bapat, V. Kulathumani, M. Sridharan, H. Zhang, and H. Cao, "Kansei: A Testbed for Sensing at Scale," in Proc. 4th Symposium on Information Processing in Sensor Networks, USA, April 2006.

[6] MistLab Testbed: http://mistlab.csail.mit.edu/

[7] M. Ott, I. Seskar, R. Siracusa, and M. Singh, "ORBIT Testbed Software Architecture: Supporting Experiments as a Service," in Proc. IEEE Tridentcom, Italy, February 2005.

[8] D. Johnson, D. Flickinger, T. Stack, R. Ricci, L. Stoller, R. Fish, K. Webb, M. Minor, and J. Lepreau, "Emulab's Wireless Sensor Net Testbed: True Mobility, Location Precision, and Remote Access," in Proc. 3rd International Conference on Embedded Networked Sensor Systems, 2005.

[9] WISEBED - Wireless Sensor Network Testbed: http://www.wisebed.eu/

[10] J. Albesa, R. Casas, M. T. Penella, and M. Gasulla, "REALnet: An environmental WSN Testbed," in Proc. International Conference on Sensor Technologies and Applications, 2007, pp. 502-507.

[11] K. Iwanicki, A. Gaba, and M. V. Steen, "KonTest: A Wireless Sensor Network Testbed at Vrije Universiteit Amsterdam," Vrije Universiteit Amsterdam, Technical Report IR-CS-045, The Netherlands, Aug. 2008.

[12] A. Hergenr¨oder, J. Horneber, D. Meier, P. Armbruster, and M. Zitterbart, "Demo Abstract: Distributed Energy Measurements in Wireless Sensor Networks," in Proc. SenSys'09, USA, Nov. 2009. http://doc.tm.uka.de/SANDbed_Poster.pdf

[13] H. Alzaid, and S. Abanmi, "A Wireless Sensor Networks Test-bed for the Wormhole Attack," International Journal of Digital Content Technology and its Applications, vol. 3, no. 3, pp.19-27, Sept. 2009.

[14] U. Kumar, A. Ranjan, V. Jalan, P. Mundra, and P. Ranjan, "CENSE: A Modular Sensor Network Testbed," in Proc. National Conference on Embedded Systems, India, Feb. 2006.