MIDDLEWARE FOR WIRELESS SENSOR NETWORK VIRTUALIZATION

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This thesis is dedicated to my late beloved grandmother Zatoon Bibi for her love, concern and support to make sure I achieve higher targets.

This thesis is dedicated to my beloved mother Rukhsana Khalid and father Khalid Hussain. This thesis is a testimony of the efforts of my parents, how they prayed and struggled for me to get the best things of both worlds.

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ABSTRACT

Sensor and network virtualization technology are used in smart home, smart grid, smart city and many other applications of Internet of Things (IoT) that deploy Wireless Sensor Network (WSN) to facilitate multiple sensor data transmission over multiple networks. Existing WSNs are designed for a specific application running on low data rate network. The challenge is how to ensure multiple sensor data for multiple applications be transmitted over multiple heterogeneous networks having different transmission rates while ensuring Quality-of-Service (QoS). The research has developed a middleware that provides sensor and network virtualization with guaranteed QoS. The middleware was designed comprising of two layers: Application Dependent Layer Middleware (ADLM) and Network Dependent Layer Middleware (NDLM). The ADLM combined multiple sensor data to form services based of Service Oriented Application (SOA). It is comprised of service handling manager that combines various sensor data and form services, QoS manager that assigns priority and service scheduling manager that forwards the service frames. The NDLM facilitated seamless transmissions of various service data over multiple heterogeneous networks. It consists of hypervisor which is composed of flowvisor and the powervisor. The flowvisor is madeup of transmit and routing managers responsible for routing and transmitting service packets. The powervisor consists of a resource manager that determines and selects the node with the highest battery power. The middleware was implemented and evaluated on a real experimental testbed. The experimental results showed that the middleware increased throughput by 8.7% and reduced the numbers of packets transmissions from the node by 68.7% compared to proxy middleware using SOA. In addition, end-to-end transmission delay was reduced by 85.2% when compared to SenShare using SOA. The flowvisor at the gateway decreased the waiting time of packets in the queue by 59.8%, when the flowvisor raised the output rate up to 2.5 times the maximum arrival rate of WSN packets. The powervisor increased the node’s life time by 17.6% when compared to VITRO by limiting the transmission power to the existing battery voltage level. In brief, the middleware has provided guaranteed QoS by increasing throughput, reducing end-to-end delay and minimizing energy consumption. The middleware is highly recommended for IoT applications such as smart city and smart grid.

ABSTRAK

Penderia dan teknologi kemayaan rangkaian digunakan di dalam rumah pintar, grid pintar, bandar pintar dan banyak aplikasi lain untuk objek rangkaian internet (IoT) yang mengatur kedudukan rangkaian penderia tanpa wayar (WSN) untuk memudahkan penghantaran berbilang data penderia melalui berbilang rangkaian. WSN sedia ada direka untuk aplikasi khusus berfungsi pada rangkaian data berkadaran rendah. Cabarannya adalah bagaimana memastikan data berbilang penderia untuk berbilang aplikasi yang akan dihantar melalui berbilang rangkaian berlainan mempunyai kadar penghantaran berbeza sambil menjamin kualiti perkhidmatan (QoS). Penyelidikan ini telah membangunkan satu perisian tengah yang menyediakan penderia dan teknologi kemayaan dengan QoS yang terjamin. Perisian tengah yang dicadangkan adalah direka dengan mempunyai dua lapisan; lapisan perisian tengah bersandarkan aplikasi (ADLM), dan lapisan perisian tengah bersandarkan rangkaian (NDLM). ADLM itu menggabungkan data berbilang penderia untuk membentuk perkhidmatan berdasarkan aplikasi berorientasikan perkhidmatan (SOA). Ianya mengandungi pengurus pengendali perkhidmatan yang mengabungkan data pelbagai penderia dan membentuk perkhidmatan, pengurus QoS yang menetapkan tahap keutamaan dan pengurus penjadualan perkhidmatan yang menghantar kerangka perkhidmatan. NDLM itu memudahkan penghantaran selenjar untuk pelbagai data perkhidmatan melalui berbilang rangkaian berlainan. Ianya mengandungi *hypervisor* yang terdiri daripada *flowvisor* dan *powervisor*. *Flowvisor* adalah dibuat daripada pengurus penghantaran dan pengurus penghalaan yang bertanggungjawab untuk penghalaan dan penghantaran paket. *Powervisor* pula mengandungi pengurus sumber yang menentukan dan memilih nod yang mempunyai kuasa bateri paling tinggi. Perisian tengah ini telah dilaksanakan dan dinilai pada eksperimen tapak uji yang sebenar. Hasil eksperimen menunjukkan perisian tengah itu meningkatkan daya pemprosesan sebanyak 8.7% dan mengurangkan bilangan paket penghantaran dari nod sebanyak 68.7% berbanding dengan proksi perisian tengah menggunakan SOA. Selanjutnya, lengah penghantaran hujung-ke-hujung telah dikurangkan sebanyak 85.2% apabila dibandingkan dengan SenShare yang menggunakan SOA. *Flowvisor* pada get laluan mengurangkan masa menunggu paket dalam giliran sebanyak 59.8% apabila *flowvisor* meningkatkan kadar keluaran setinggi 2.5 kali ganda kadar ketibaan maksimum paket WSN. *Powervisor* meningkatkan kadar tempoh hayat nod sebanyak 17.6% berbanding dengan VITRO dengan menghadkan kuasa penghantaran kepada kadar voltan bateri semasa. Secara ringkasnya, perisian tengah yang dicadangkan telah membuktikan jaminan QoS dengan meningkatkan daya pemprosesan, mengurangkan masa lengah hujung-ke-hujung dan meminimumkan penggunaan tenaga. Perisian tengah ini adalah sangat disarankan untuk aplikasi IoT seperti bandar pintar, grid pintar dan sebagainya.

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LIST OF ABBREVIATIONS

3G	-	Third Generation
6LowPAN	-	IPv6 over Low Power Wireless Personal Area Networks
AAL	-	Ambient Assisted Living
ADLM	-	Application Dependent Layer Middleware
ADSLM	-	Application Dependent Sub-Layer Middleware
AOP	-	Agent Oriented Programming
AP	-	Access Point
API	-	Application Programming Interface
CMC	-	Communication Manager Component
CPU	-	Central Processing Unit
CBSE	-	Component Based Software Engineering
DHCP	-	Dynamic Host Configuration Protocol
FIRE	-	Future Internet Research and Experimentation
FIFO	-	First In First Out
HAL	-	Hardware Abstrsction Layer
HVAC	-	Heating Ventilation and Air Conditioning
IEEE	-	Institute of Electrical and Electronics Engineers
ISM	-	Industrial Scientific and Medical
IoT	-	Internet of Things
IoE	-	Internet of Everything
IP	-	Internet Protocol
LTE	-	Long Term Evolution
M2M	-	Machine to Machine
NIR	-	Network Information Registry
NDLM	-	Network Dependent Layer Middleware
OOP	-	Object Oriented Programming
OS	-	Operating System

QoS	-	Qualtiy of Service
REST	-	Representational State Transfer
ROA	-	Resource Oriented Architecture
RF	-	Radio Frequency
SHAAL	-	Smart Home Ambient Assisted Living
SDSLM	-	Service Dependent Sub-Layer Middleware
SOAP	-	Simple Object Access Protocol
SWE	-	Sensor Web Enablement
SQL	-	Structured Query Language
SOA	-	Service Oriented Application
TCP	-	Transmission Control Protocol
UDP	-	User Datagram Protocol
URI	-	Uniform Resource Identifier
WSN	-	Wireless Sensor Network
XML	-	Extensible Markup Language

LIST OF SYMBOLS

α	-	protocol overhead
β	-	Throughput
ρ	-	Utilization factor
λ	-	Arrival rate of the packets
μ	-	Output rate of the packet
G	-	General Distribution
M	-	Markovian Distribution
S	-	Number of Processing Elements
V	-	Serve time of a Single Packet
$\overline{V}$	-	Mean Time to Serve a Single Packet
H_B	-	Header Bytes
N_q	-	Number of Packets in the Queue
N_S	-	Number of Sensors
N_S	-	Number of Packets in the System
N_{AP}	-	Number of Applications
P_B	-	Payload Bytes
P_0	-	Probability of idle Queue
T_Q	-	Time in the Queue
T_T	-	Total Time
T_{BN}	-	Buffering Time ta Node
T_{BU}	-	Buffering Time ta User node
T_{GU}	-	Transmission Time form Node to User Node
T_{NG}	-	Transmission Time form Node to Gateway
T_{RS}	-	Time to Read Sensor
T_{PGU}	-	Propogation Time form Node to User Node
T_{PNG}	-	Propogation Time form Node to Gateway
T_{PGS}	-	Time Propogation form Gateway to Server

W_q	-	Waiting Time in Queue
W_S	-	Waiting Time in System
W_{HS}	-	Waiting Time of High Priority Packets in System
W_{LS}	-	Waiting Time of Low Priority Packets in System
W_{LQ}	-	Waiting Time of Low Priority Packets in Queue
W_{HQ}	-	Waiting Time of High Priority Packets in Queue
W_{MQ}	-	Waiting Time of Medium Priority Packets in Queue
W_{MS}	-	Waiting Time of Medium Priority Packets in System

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CHAPTER 1

INTRODUCTION

1.1 Background

The trend in wireless networks, sensor devices and embedded technologies has led to the increasingly interconnected devices. The rapid growth in the interconnected devices using wireless sensor networks (WSN) is the basis of Internet of Thing (IoT) [1]. IoT is the concept where large and small federated WSNs are seamlessly connected to each other. IoT provides a potential business opportunity for IoT infrastructure providers, service providers and software developers. The future market for IoT is expected to reach 212 billion globally by 2020 [2].

Wireless Sensor Network (WSNs) are made up of sensing nodes mounted with sensors and wireless transceivers that communicate with each other through multi hops transmission. The sensing nodes monitor the physical conditions using sensors, and transfers the information through the wireless medium. WSNs have immensely been deployed in the fields of health care, smart home, assisted living, environment monitoring, structural monitoring, military, security systems and etc.

Cloud computing and WSN play a significant role in IoT. Sensed data in the WSN is uploaded to the cloud which has large storage, ample power and processing capabilities. The web interaction technique is used in cloud computing to allow data to be accessed globally through the Internet. Smart home is one of the applications in IoT. Smart home is a new automation potential that can increase the standard of living of home residents. It provides connectivity to household appliances mounted with sensors nodes and actuators in the form of WSN that are linked to the cloud and the outside world. Smart home technology includes home security, home power management, home appliances control, assisted living, HVAC control, fire detection and environment monitoring to raise the living standard of the residents. Homes are getting smarter and increase the comfort level of elder residents at home with the advancement in smart home technology [3].

Ambient assisted living (AAL) is a concept that assists elderly or needy residents at home based on WSN. AAL constantly monitors the health condition of the elder residents at home using tiny sensor nodes, and tries to minimize the damage caused by the health risks such as a fall, a stroke, heart attack, or any other disasters event effecting elders at home [4]. In AAL the body of elderly resident at home is mounted with the wearable sensors to monitor SpO2, heartbeat, blood pressure, movements and fall detection. The paradigm of smart home and ambient assisted living focuses on home automating and assisting elderly and physically disable residents at home.

AAL is important due to the fact that roughly about 20% of the world's population will be age 60 or older by 2050 [5, 6]. Many of the elderly people face the age-related diseases such as Parkinson and Alzheimer that cause cognitive decay, limitations on the physical activities, vision disorders and hearing [7]. Therefore, the amount of caregivers has to be increased to cater the problems of elderly people. Smart home and ambient assisted living is an alternative to the caregivers such as elderly home or hospital, by allowing the elderly and needy personals staying at home while receiving medical treatment remotely.

Smart home and ambient assisted living application may use Zigbee, WiFi and cellular data network such as 3G, 4G and LTE as the network for communications. WSN has been designed to accommodate and support a specific application [8, 9]. However, Smart home and ambient assisted living is based on multiple applications with diverse requirements. In order to support multiple applications, multiple WSNs have to be deployed for running each separate specific application. WSNs are equipped with low power short range wireless transceiver based on IEEE 802.15.4 recommendations for local data transmission. However, smart home and ambient assisted living may require sensed data to be sent through multiple heterogeneous networks to reach far distance destination. In order to support data transmission over multiple heterogeneous networks, the existing approach is to use a router or gateway where data are queued and wait for transmission to the specific network.

However, this solution is very less attractive due to the high cost of new WSN deployment and space occupations. The future of smart home and ambient assisted living lies in the virtualization of different hardware, software and services on a single platform. Virtualization creates an environment in embedded and sensor networks, by which efficient sharing of resources, services and networks is achieved. Virtualization combines different hardware and software on a platform along with the network functionalities to control and administrate all the network resources [10]. The goal of virtualization is to provide users with seamless access to the sensor data and allow efficient utilization of the resources.

Virtualization can be divided into two main categories, sensor virtualization and network virtualization. Sensor virtualization supports multiple applications on a single WSN. Network virtualization provides seamless data transmission over heterogeneous networks. In order to practically realize smart home ambient assisted living there is a need to come up with network designs that have the capabilities of achieving both the sensor virtualization and the network virtualization. In this work sensor and network virtualization for smart home ambient assisted living will be developed using middleware. The middleware is developed through the software programming of the heterogeneous network.

1.2 Problem Statement

WSN are deployed for a particular application that is "*fit-for-purpose*". Network deployed for a single application can only serve a specific application due to the tight coupling between application and network [11, 12]. The concern is separate network for each application will lead to increase in the number of WSN nodes and networks deployment [11, 13, 14]. The future IoT applications requires WSN that are "*fit for multipurpose*" [11]. However, different applications use different radio technologies and have different application requirements. The challenge is to design and implement efficient, holistic middleware that provides both sensor and network virtualization on multiple radio networks.

Middleware for WSN virtualization faces overhead challenges caused by the additional middleware layer [10, 11, 14–17]. Therefore, inclusion of the middleware incurs overhead that may reduce the efficiency of WSN and thus degrade the QoS of WSN. The challenge is to design middleware that can minimize degradation of QoS in WSN in terms of energy efficiency, throughput and delay. Furthermore, heterogeneous networks' integration and efficient management are still immature in the paradigm of WSN virtualization [12, 17–19].

1.3 Objectives of the Thesis

The main objective of the thesis is to design and implement middleware for smart ambient assisted living defined as SHAAL. The purpose of the middleware is to ensure QoS for SHAAL network that will be used to control and monitor home appliances and assist the elderly and caregiver at home. In addition the middleware should provide flexibility, modularity, robustness, scalability, extensibility and ease of programming in WSN for applications linked to IoT. In order to develop the middleware that can ensure QoS in sensor and network virtualization, the specific objectives include;

I. To design middleware based on service oriented application approach to provide sensor virtualization.

II. To design middleware that facilitates transmission over multiple radio networks for network virtualization.

III. To implement and evaluate middleware in the real experimental testbed environment.

In this work the QoS or the performance of SHAAL network depends on the throughput, node's life time, end to end delay and energy efficiency. The performance of the SHAAL network with the proposed middleware is evaluated in the real experimental testbed.

1.4 Scope of the Thesis

The middleware layer is assumed to sit exactly between the application layer and network layer. The middleware resides on the sensor nodes, the gateway and the user application devices. For the evaluation of the middleware, real testbed has been setup, considering home environment and using the sensor nodes mounted with multiple sensors. The testbed is set up in the laboratory by placing all the sensor nodes in stationary positions. Furthermore, the testbed comprises of multiple low power, low processing sensor nodes. Testbed nodes are based on IEEE 802.15.4 and WiFi networks, which use industrial, scientific and medical (ISM) radio frequency band at 2.4 GHz. Sensor nodes use WiFi and IEEE 802.15.4 network to communicate with the gateway. All nodes using WiFi network are based on IPv4 addressing scheme.

Furthermore, the 3G network is used to communicate to the cloud server by the gateway.

The sensor nodes are based on different Operating System (OS); TelG node is based on WiseOS and Raspberry-pi node is based on Embedded Linux. For the gateway UDOO board is used, that is a high processing power device based on Embedded Linux. TelG sensor nodes are programmed using C programming language and gateway is programmed using python programming language. TelG nodes are mounted with XBEE 802.15.4 and XBEE WiFi modules. The cloud server has not been setup in the laboratory; rather Ubidots cloud server is used for the experimental setup. The middleware at the gateway uses RESTful approach to communicate with the cloud server over 3G. Cloud server is not used to manage multiple WSNs; rather it is used only for the storage purposes.

1.5 Research Contributions

The main contributions of the work are the development of the middleware layer. The middleware layer allows multiple applications to run over multiple networks. Middleware takes a holistic approach and provides support for sensor virtualization and network virtualization. The specific contribution includes.

- Application Dependent Layer Middleware (ADLM) is designed based on the Service Oriented Application (SOA) that combines multiple sensors' data and form services that increases the throughput. The ADLM assigns priority to each service frame of IEEE 802.15.4 and WiFi network, which reduces the queuing delay of high priority packets as they are served first.
- Network Dependent Layer Middleware (NDLM) is designed that manages multiple networks and the battery power of the sensor node by adjusting the transmission power of the node's RF module according to the current battery voltage level that increases the node's life time. It is also responsible to choose the best next hop node for routing the service packet to the gateway.
- Hypervisor is designed on the NDLM at the gateway. The hypervisor hides the differences of multiple networks and enables WSNs' nodes to communicate seamlessly with other network nodes and the cloud server through the Internet. The flowvisor reduces the transmission delay by increasing the output rate of the

queue. Powervisor chooses the nodes with the highest battery power for service data transmissions.

1.6 Significance of the Research

Middleware for sensor and network virtualization can guarantee an effective implementation of multiple IoT applications. The capability of supporting multiple applications reduces the proliferation of networks and devices. Furthermore, with multi network and multi radio support, it is easy to add a wide range of devices into already installed networks. Therefore, the middleware reduces the cost of network deployment significantly, and plays a key role in making businesses successful by lowering costs for the end users.

Middleware provides extensibility, scalability, robustness, energy awareness and ease of programming that can play a significant role in the uplifting the performance of IoT applications like; industrial networks, security systems, smart grid, structural monitoring, smart transportation and health care etc. Supporting multiple heterogeneous networks, middleware contributes to IoT where large heterogeneous networks are to be federated.

1.7 Thesis Outline

This thesis consists of six chapters and is organized as follows:

Chapter 2 studies and reviews the background knowledge and previous works carried out related to sensor and network virtualization. It presents the analysis of the middleware for WSN virtualization and its strategies. It clearly presents the previous research works, and highlights the shortcomings of the previous efforts made in the paradigm of sensor and network virtualization. In this respect, it first presents the introduction of WSN, smart home and assisted living technologies. It highlights the concept of sensor virtualization and network virtualization. Furthermore, in depth critical review of relevant literature is presented. Furthermore, the programming paradigms and operating systems used for WSN middleware development are investigated. Moreover, an analysis of the previous testbeds is made, and the

REFERENCES

1. Gubbi, J., Buyya, R., Marusic, S. and Palaniswami, M. Internet of Things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems*, 2013. 29(7): 1645–1660.

2. Atzori, L., Iera, A. and Morabito, G. The internet of things: A survey. *Computer networks*, 2010. 54(15): 2787–2805.

3. Viani, F., Robol, F., Polo, A., Rocca, P., Oliveri, G. and Massa, A. Wireless Architectures for Heterogeneous Sensing in Smart Home Applications: Concepts and Real Implementation. *Proceedings of the IEEE*, 2013. 101(11): 2381–2396. ISSN 0018-9219. doi:10.1109/JPROC.2013.2266858.

4. Mukhopadhyay, S. C., Suryadevara, N. K. and Rayudu, R. K. Are Technologies Assisted Homes Safer for the Elderly? In: *Pervasive and Mobile Sensing and Computing for Healthcare*. Springer. 51–68. 2013. ISBN 3642325378.

5. Rashidi, P. and Mihailidis, A. A Survey on Ambient Assisted Living Tools for Older Adults. *IEEE Journal of Biomedical and Health Informatics*, 2013. 17(3): 11.

6. Fleck, S. and Straß er, W. Smart camera based monitoring system and its application to assisted living. *Proceedings of the IEEE*, 2008. 96(10): 1698–1714.

7. Vergados, D. D. Service personalization for assistive living in a mobile ambient healthcare-networked environment. *Personal and Ubiquitous Computing*, 2010. 14(6): 575–590.

8. Khan, I., Belqasmi, F., Glitho, R. and Crespi, N. A multi-layer architecture for wireless sensor network virtualization. *Wireless and Mobile Networking Conference (WMNC), 2013 6th Joint IFIP*. IEEE. 2013. ISBN 1467356158. 1–4.

9. Khan, I. Design and analysis of virtualization framework for Wireless Sensor Networks. *World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2013 IEEE 14th International Symposium and Workshops on a*. IEEE. 2013.

ISBN 1467358274. 1–2.

10. Islam, M. M., Hassan, M. M., Lee, G.-W. and Huh, E.-N. A survey on virtualization of wireless sensor networks. *Sensors*, 2012. 12(2): 2175–2207.

11. Leontiadis, I., Efstratiou, C., Mascolo, C. and Crowcroft, J. SenShare: transforming sensor networks into multi-application sensing infrastructures. In: *Wireless Sensor Networks*. Springer. 65–81. 2012. ISBN 3642281680.

12. Sarakis, L., Zahariadis, T., Leligou, H.-C. and Dohler, M. A framework for service provisioning in virtual sensor networks. *EURASIP Journal on Wireless Communications and Networking*, 2012. 2012(1): 1–19.

13. Kulkarni, P., Ganesan, D., Shenoy, P. and Lu, Q. SensEye: a multi-tier camera sensor network. *Proceedings of the 13th annual ACM international conference on Multimedia*. ACM. 2005. ISBN 1595930442. 229–238.

14. Khan, I., Belqasmi, F., Glitho, R., Crespi, N., Morrow, M. and Polakos, P. Wireless Sensor Network virtualization: Early architecture and research perspectives. *IEEE Network*, 2015. 29(3): 104–112.

15. Malan, D., Fulford-Jones, T., Welsh, M. and Moulton, S. Codeblue: An ad hoc sensor network infrastructure for emergency medical care. *International workshop on wearable and implantable body sensor networks*. 2004, vol. 5.

16. Fok, C.-L., Roman, G.-C. and Lu, C. Enhanced coordination in sensor networks through flexible service provisioning. *Coordination Models and Languages*. Springer. 2009. ISBN 3642020526. 66–85.

17. Islam, M. M., Lee, J. H. and Huh, E.-N. An Efficient Model for Smart Home by the Virtualization of Wireless Sensor Network. *International Journal of Distributed Sensor Networks*, 2013. 2013: 10. doi:10.1155/2013/168735. URL `http://dx.doi.org/10.1155/2013/168735`.

18. Liang, C. and Yu, F. R. Wireless network virtualization: A survey, some research issues and challenges. *IEEE Communications Surveys & Tutorials*, 2015. 17(1): 358–380.

19. Merentitis, A., Zeiger, F., Huber, M., Frangiadakis, N., Mathioudakis, K., Sasloglou, K., Mazarakis, G., Gazis, V. and Boufidis, Z. WSN Trends: Sensor Infrastructure Virtualization as a Driver Towards the Evolution of the Internet of Things. *UBICOMM 2013, The Seventh International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies*. 2013. ISBN 1612082890. 113–118.

20. Yick, J., Mukherjee, B. and Ghosal, D. Wireless sensor network survey.

Computer networks, 2008. 52(12): 2292–2330.

21. Abdulla, R. and Ismail, W. Survey of WSN technology based reliable and efficient active RFID. *Communications (MICC), 2013 IEEE Malaysia International Conference on*. IEEE. 2013. 116–121.

22. Thompson, R., Zhou, G., Lu, L., Krishnamurthy, S., Dong, H., Qi, X., Li, Y., Keally, M. and Ren, Z. A Self-Adaptive Spectrum Management Middleware for Wireless Sensor Networks. *Wireless personal communications*, 2013. 68(1): 131–151.

23. Li, L., Xiaoguang, H., Ke, C. and Ketai, H. The applications of wifi-based wireless sensor network in internet of things and smart grid. *2011 6th IEEE Conference on Industrial Electronics and Applications*. IEEE. 2011. ISBN 1424487544. 789–793.

24. Khan, D. U., Siek, K. A., Meyers, J., Haverhals, L. M., Cali, S. and Ross, S. E. Designing a personal health application for older adults to manage medications. *Proceedings of the 1st ACM International Health Informatics Symposium*. ACM. 2010. ISBN 1450300308. 849–858.

25. Selvaratnam, D. P., Bakar, N. A., Idris, N. A. H. and dan Pengurusan, F. E. The health determinants of elderly malaysian popultion.

26. Jayasumana, A. P., Han, Q. and Illangasekare, T. H. Virtual sensor networks-A resource efficient approach for concurrent applications. *Information Technology, 2007. ITNG'07. Fourth International Conference on*. IEEE. 2007. ISBN 0769527760. 111–115.

27. Liu, L., Kuo, S. M. and Zhou, M. Virtual sensing techniques and their applications. *Networking, Sensing and Control, 2009. ICNSC'09. International Conference on*. IEEE. 2009. ISBN 1424434912. 31–36.

28. Levis, P. and Culler, D. Maté: A tiny virtual machine for sensor networks. *ACM Sigplan Notices*. ACM. 2002, vol. 37. ISBN 1581135742. 85–95.

29. Zahariadis, T., Sarakis, L., Trakadas, P., Leligou, H. C. and Karkazis, P. Sensor Networks Virtualisation for efficient Smart Application Development.

30. Sonule, M. G. and Nikam, S. Role of Sensor Virtualization in Wireless Sensor Networks.

31. Madria, S., Kumar, V. and Dalvi, R. Sensor Cloud: A Cloud of Virtual Sensors. 2013.

32. Yarvis, M., Kushalnagar, N., Singh, H., Rangarajan, A., Liu, Y. and Singh, S. Exploiting heterogeneity in sensor networks. *INFOCOM 2005. 24th Annual*

Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE. IEEE. 2005, vol. 2. ISBN 0780389689. 878–890.

33. Aberer, K., Hauswirth, M. and Salehi, A. Infrastructure for Data Processing in Large-Scale Interconnected Sensor Networks. *Mobile Data Management, 2007 International Conference on*. 2007. 198–205. doi:10.1109/MDM.2007.36.

34. Ruzzelli, A. G., O'Hare, G., Jurdak, R. and Tynan, R. Advantages of Dual Channel MAC for Wireless Sensor Networks. *Communication System Software and Middleware, 2006. Comsware 2006. First International Conference on*. 2006. 1–3. doi:10.1109/COMSWA.2006.1665223.

35. Chowdhury, N. M. and Boutaba, R. A survey of network virtualization. *Computer Networks*, 2010. 54(5): 862–876.

36. Bandyopadhyay, S. and Coyle, E. J. An energy efficient hierarchical clustering algorithm for wireless sensor networks. *INFOCOM 2003. Twenty-Second Annual Joint Conference of the IEEE Computer and Communications. IEEE Societies*. IEEE. 2003, vol. 3. ISBN 0780377524. 1713–1723.

37. Ansari, J., Zhang, X. and Mahonen, P. Multi-radio medium access control protocol for wireless sensor networks. *International Journal of Sensor Networks*, 2010. 8(1): 47–61.

38. Je, M., Liow, T.-Y., Chang, H.-K., Bhattacharya, S. and Kwong, D.-L. Future mobile society beyond Moore's Law. *Solid-State Circuits Conference (A-SSCC), 2013 IEEE Asian*. IEEE. 2013. ISBN 1479902772. 1–4.

39. Lymberopoulos, D., Priyantha, N. B., Goraczko, M. and Zhao, F. Towards energy efficient design of multi-radio platforms for wireless sensor networks. *Information Processing in Sensor Networks, 2008. IPSN'08. International Conference on*. IEEE. 2008. ISBN 0769531571. 257–268.

40. Hughes, D., Bencomo, N., Morin, B., Huygens, C., Shen, Z. and Man, K. L. S-Theory: A Unified Theory of Multi-paradigm Software Development. In: *Grid and Pervasive Computing*. Springer. 715–722. 2013. ISBN 3642380263.

41. Navarro, M., Antonucci, M., Sarakis, L. and Zahariadis, T. VITRO architecture: Bringing Virtualization to WSN world. *Mobile Adhoc and Sensor Systems (MASS), 2011 IEEE 8th International Conference on*. IEEE. 2011. ISBN 1457713454. 831–836.

42. Islam, M. M. and Huh, E.-N. Virtualization of wireless sensor network:

Smart house perspective.

43. Yu, Y., Rittle, L. J., Bhandari, V. and LeBrun, J. B. Supporting concurrent applications in wireless sensor networks, 2006. doi:10.1145/1182807.1182822.

44. Efstratiou, C., Leontiadis, I., Mascolo, C. and Crowcroft, J. A shared sensor network infrastructure. *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*. ACM. 2010. ISBN 1450303447. 367–368.

45. Desnoyers, P., Ganesan, D., Li, H., Li, M. and Shenoy, P. J. PRESTO: A Predictive Storage Architecture for Sensor Networks. *HotOS*. 2005.

46. Yao, Y. and Gehrke, J. The cougar approach to in-network query processing in sensor networks. *ACM Sigmod Record*, 2002. 31(3): 9–18.

47. Madden, S. R., Franklin, M. J., Hellerstein, J. M. and Hong, W. TinyDB: an acquisitional query processing system for sensor networks. *ACM Transactions on database systems (TODS)*, 2005. 30(1): 122–173.

48. Levis, P. A., Patel, N., Culler, D. and Shenker, S. *Trickle: A self regulating algorithm for code propagation and maintenance in wireless sensor networks*. Computer Science Division, University of California. 2003.

49. Shneidman, J., Pietzuch, P., Ledlie, J., Roussopoulos, M., Seltzer, M. and Welsh, M. *Hourglass: An infrastructure for connecting sensor networks and applications*. Technical report. 2004.

50. Rouached, M., Baccar, S. and Abid, M. RESTful sensor web enablement services for wireless sensor networks. *Services (SERVICES), 2012 IEEE Eighth World Congress on*. IEEE. 2012. ISBN 1467330531. 65–72.

51. Murphy, A. and Heinzelman, W. Milan: Middleware linking applications and networks. *University of Rochester, Tech. Rep. TR-795*, 2002.

52. Heinzelman, W. B., Murphy, A. L., Carvalho, H. S. and Perillo, M. A. Middleware to support sensor network applications. *Network, IEEE*, 2004. 18(1): 6–14.

53. Glatz, P. M., Hormann, L. B., Steger, C. and Weiss, R. MAMA: Multi-applicationmiddleware for efficient wireless sensor networks. *Telecommunications (ICT), 2011 18th International Conference on*. IEEE. 2011. ISBN 1457700255. 1–8.

54. Domingues, J., Damaso, A., Nascimento, R. and Rosa, N. An energy-aware middleware for integrating wireless sensor networks and the internet.

International Journal of Distributed Sensor Networks, 2011. 2011.

55. Paulino, H. and Santos, J. R. A middleware framework for the web integration of sensor networks. In: *Sensor Systems and Software*. Springer. 75–90. 2011. ISBN 3642235824.

56. Wood, A. D., Selavo, L. and Stankovic, J. A. SenQ: An embedded query system for streaming data in heterogeneous interactive wireless sensor networks. In: *Distributed computing in sensor systems*. Springer. 531–543. 2008. ISBN 3540691693.

57. Corsini, P., Masci, P. and Vecchio, A. Configuration and tuning of sensor network applications through virtual sensors. *Pervasive Computing and Communications Workshops, 2006. PerCom Workshops 2006. Fourth Annual IEEE International Conference on*. IEEE. 2006. ISBN 0769525202. 5 pp.–320.

58. Alam, S., Chowdhury, M. M. R. and Noll, J. Virtualizing sensor for the enablement of semantic-aware internet of things ecosystem. *Guest Editors*, 2010: 41.

59. Frantti, T., Hietalahti, H. and Savola, R. Requirements of secure WSN-MCN edge router. *Information Networking (ICOIN), 2013 International Conference on*. IEEE. 2013. ISBN 1467357405. 210–215.

60. Tajmajer, T., Lalis, S., Koutsoubelias, M., Pruszkowski, A., Domaszewicz, J., Nati, M. and Gluhak, A. Node/Proxy portability: Designing for the two lives of your next WSAN middleware. *Journal of Systems and Software*, 2016. 117: 366–383.

61. Wan, J., Li, D., Zou, C. and Zhou, K. M2M communications for smart city: an event-based architecture. *Computer and Information Technology (CIT), 2012 IEEE 12th International Conference on*. IEEE. 2012. ISBN 1467348732. 895–900.

62. Wu, G., Talwar, S., Johnsson, K., Himayat, N. and Johnson, K. D. M2M: From mobile to embedded internet. *Communications Magazine, IEEE*, 2011. 49(4): 36–43.

63. Zhang, Y., Yu, R., Xie, S., Yao, W., Xiao, Y. and Guizani, M. Home M2M networks: Architectures, standards, and QoS improvement. *Communications Magazine, IEEE*, 2011. 49(4): 44–52.

64. Wang, Z. and Xu, X. Smart Home M2M Networks Architecture. *Mobile Ad-hoc and Sensor Networks (MSN), 2013 IEEE Ninth International Conference on*. IEEE. 2013. ISBN 0769551599. 294–299.

65. Riker, A., Granjal, J., Curado, M. and Monteiro, E. Middleware Group Communication Mechanisms in M2M environments. *2nd Joint ERCIM eMobility and MobiSense Workshop*. 46.

66. Glitho, R. H. Application architectures for machine to machine communications: Research agenda vs. state-of-the art. *Broadband and Biomedical Communications (IB2Com), 2011 6th International Conference on*. 2011. 1–5. doi:10.1109/IB2Com.2011.6217900.

67. Seung Hwan Shi R. Rim Haw, Y. K. Intelligent M2M network using healthcare sensors. *Network Operations and Management Symposium (APNOMS), 2012 14th Asia-Pacific*, 2011: 1–4.

68. Tsiatsis, V., Gluhak, A., Bauge, T., Montagut, F., Bernat, J., Bauer, M., Villalonga, C., Barnaghi, P. and Krco, S. The SENSEI real world internet architecture. *Towards the Future Internet-Emerging Trends from European Research*, 2010: 247–256.

69. Majeed, A. and Zia, T. A. Multi-set architecture for multi-applications running on wireless sensor networks. *Advanced Information Networking and Applications Workshops (WAINA), 2010 IEEE 24th International Conference on*. IEEE. 2010. ISBN 1424467012. 299–304.

70. Wang, Q., Shin, W., Liu, X., Zeng, Z., Oh, C., AlShebli, B. K., Caccamo, M., Gunter, C. A., Gunter, E. and Hou, J. I-Living: An open system architecture for assisted living. *Systems, Man and Cybernetics, 2006. SMC'06. IEEE International Conference on*. IEEE. 2006, vol. 5. ISBN 1424400996. 4268–4275.

71. Evensen, P. l. and Meling, H. SenseWrap: A service oriented middleware with sensor virtualization and self-configuration. *Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), 2009 5th International Conference on*. IEEE. 2009. ISBN 142443517X. 261–266.

72. Aberer, K., Hauswirth, M. and Salehi, A. A middleware for fast and flexible sensor network deployment. *Proceedings of the 32nd international conference on Very large data bases*. VLDB Endowment. 2006. 1199–1202.

73. Dai, H. and Han, R. Unifying micro sensor networks with the internet via overlay networking [wireless networks]. *Local Computer Networks, 2004. 29th Annual IEEE International Conference on*. IEEE. 2004. 571–572.

74. Lei, S., Xu, H., Xiaoling, W., Lin, Z., Cho, J. and Lee, S. VIP bridge: Integrating several sensor networks into one virtual sensor network. *International Conference on Internet Surveillance and Protection (ICISP&#*

146; 06). IEEE. 2006. 2–2.

75. Aberer, K., Hauswirth, M. and Salehi, A. The Global Sensor Networks middleware for efficient and flexible deployment and interconnection of sensor networks. *Ecole Polytechnique Fdrale de Lausanne (EPFL), Tech. Rep. LSIR-REPORT-2006-006*, 2006.

76. Chen, C. and Ma, J. MEMOSEN: multi-radio enabled mobile wireless sensor network. *20th International Conference on Advanced Information Networking and Applications-Volume 1 (AINA'06)*. IEEE. 2006, vol. 2. 5–pp.

77. Starsinic, M. System architecture challenges in the home M2M network. *Applications and Technology Conference (LISAT), 2010 Long Island Systems*. IEEE. 2010. ISBN 1424455480. 1–7.

78. Shih-Hao, H., Chun-Han, C. and Chia-Heng, T. Performance evaluation of machine-to-machine (M2M) systems with virtual machines. *Wireless Personal Multimedia Communications (WPMC), 2012 15th International Symposium on*. 2012. ISBN 1347-6890. 159–163.

79. Wang, R.-C., Chang, R.-S. and Chao, H.-C. Internetworking between ZigBee/802.15. 4 and IPv6/802.3 network. *SIGCOMM Data Communication Festival*, 2007.

80. Neves, P. A. C. d. S. and Rodrigues, J. J. P. C. Internet protocol over wireless sensor networks, from myth to reality. *Journal of Communications*, 2010. 5(3): 189–196.

81. Maharrey, B. K., Lim, A. S. and Gao, S. Interconnection between IP networks and wireless sensor networks. *International Journal of Distributed Sensor Networks*, 2012. 2012.

82. Qin, P., Liu, G. and Yang, W. The Research on the Multi-Protocol Gateway. *International Journal of Computational and Engineering*: 98.

83. Emara, K. A., Abdeen, M. and Hashem, M. A gateway-based framework for transparent interconnection between WSN and IP network. *EUROCON 2009, EUROCON'09. IEEE*. IEEE. 2009. ISBN 1424438608. 1775–1780.

84. Corchado, J. M., Bajo, J., Tapia, D. I. and Abraham, A. Using heterogeneous wireless sensor networks in a telemonitoring system for healthcare. *IEEE Transactions on Information Technology in Biomedicine*, 2010. 14(2): 234–240.

85. Sugihara, R. and Gupta, R. K. Programming models for sensor networks: A

survey. *ACM Transactions on Sensor Networks (TOSN)*, 2008. 4(2): 8.

86. Farooq, M. O. and Kunz, T. Operating systems for wireless sensor networks: A survey. *Sensors*, 2011. 11(6): 5900–5930.

87. Levis, P., Madden, S., Polastre, J., Szewczyk, R., Whitehouse, K., Woo, A., Gay, D., Hill, J., Welsh, M. and Brewer, E. TinyOS: An operating system for sensor networks. In: *Ambient intelligence*. Springer. 115–148. 2005. ISBN 3540238670.

88. Dunkels, A., Gronvall, B. and Voigt, T. Contiki-a lightweight and flexible operating system for tiny networked sensors. *Local Computer Networks, 2004. 29th Annual IEEE International Conference on*. IEEE. 2004. ISBN 0769522602. 455–462.

89. Cao, Q., Abdelzaher, T., Stankovic, J. and He, T. The liteos operating system: Towards unix-like abstractions for wireless sensor networks. *Information Processing in Sensor Networks, 2008. IPSN'08. International Conference On*. IEEE. 2008. ISBN 0769531571. 233–244.

90. Hadim, S. and Mohamed, N. Middleware: Middleware challenges and approaches for wireless sensor networks. *Distributed Systems Online, IEEE*, 2006. 7(3): 1.

91. Shoham, Y. Agent-oriented programming. *Artificial intelligence*, 1993. 60(1): 51–92.

92. Jennings, N. R. Agent-oriented software engineering. In: *Multiple Approaches to Intelligent Systems*. Springer. 4–10. 1999. ISBN 3540660763.

93. Aiello, F., Fortino, G., Gravina, R. and Guerrieri, A. A java-based agent platform for programming wireless sensor networks. *The Computer Journal*, 2011. 54(3): 439–454.

94. Quaritsch, M., Rinner, B. and Strobl, B. Improved agent-oriented middleware for distributed smart cameras. *Distributed Smart Cameras, 2007. ICDSC'07. First ACM/IEEE International Conference on*. IEEE. 2007. ISBN 1424413540. 297–304.

95. Fok, C.-L., Roman, G.-C. and Lu, C. Agilla: A mobile agent middleware for self-adaptive wireless sensor networks. *ACM Transactions on Autonomous and Adaptive Systems (TAAS)*, 2009. 4(3): 16.

96. Szyperski, C. *Component software: beyond object-oriented programming*. Pearson Education. 2002. ISBN 0201745720.

97. Fielding, R. Representational state transfer. *Architectural Styles and the*

Design of Netowork-based Software Architecture, 2000: 76–85.

98. Gay, D., Levis, P., Von Behren, R., Welsh, M., Brewer, E. and Culler, D. The nesC language: A holistic approach to networked embedded systems. *Acm Sigplan Notices*. ACM. 2003, vol. 38. ISBN 1581136625. 1–11.

99. Fielding, R. T. *Architectural styles and the design of network-based software architectures*. Ph.D. Thesis. 2000.

100. Hughes, D., Thoelen, K., Horré, W., Matthys, N., Cid, J. D., Michiels, S., Huygens, C. and Joosen, W. LooCI: a loosely-coupled component infrastructure for networked embedded systems. *Proceedings of the 7th International Conference on Advances in Mobile Computing and Multimedia*. ACM. 2009. ISBN 1605586595. 195–203.

101. Schulte, C. K. and Chandy, K. M. *Event Processing: Designing IT Systems for Agile Companies*. McGraw Hill. 2009.

102. Bakshi, A., Prasanna, V. K., Reich, J. and Larner, D. The abstract task graph: A methodology for architecture-independent programming of networked sensor systems. *Proceedings of the 2005 workshop on End-to-end, sense-and-respond systems, applications and services*. USENIX Association. 2005. ISBN 1931971323. 19–24.

103. Fielding, R. T. and Taylor, R. N. Principled design of the modern Web architecture. *ACM Trans. Internet Technol.*, 2002. 2(2): 115–150. doi: 10.1145/514183.514185.

104. Stirbu, V. A restful architecture for adaptive and multi-device application sharing. *Proceedings of the First International Workshop on RESTful Design*. ACM. 2010. ISBN 1605589594. 62–65.

105. Islam, M. M. and Huh, E.-N. A Novel Data Classification and Scheduling Scheme in the Virtualization of Wireless Sensor Networks. *International Journal of Distributed Sensor Networks*, 2013. 2013.

106. Sztrik, J. Basic queueing theory. *University of Debrecen, Faculty of Informatics*, 2012. 193.

107. Coulson, G., Porter, B., Chatzigiannakis, I., Koninis, C., Fischer, S., Pfisterer, D., Bimschas, D., Braun, T., Hurni, P. and Anwander, M. Flexible experimentation in wireless sensor networks. *Communications of the ACM*, 2012. 55(1): 82–90.

108. Baumgartner, T., Chatzigiannakis, I., Danckwardt, M., Koninis, C., Kröller, A., Mylonas, G., Pfisterer, D. and Porter, B. Virtualising testbeds to

support large-scale reconfigurable experimental facilities. In: *Wireless Sensor Networks*. Springer. 210–223. 2010. ISBN 3642119166.

109. Boano, C. A., Romer, K., Brown, J., Roedig, U. and Zuniga, M. A. Demo abstract: A testbed infrastructure to study the impact of temperature on WSN. *Pervasive Computing and Communications Workshops (PERCOM Workshops), 2014 IEEE International Conference on*. IEEE. 2014. 154–156.

110. Hellbruck, H., Pagel, M., Kroller, A., Bimschas, D., Pfisterer, D. and Fischer, S. Using and operating wireless sensor network testbeds with WISEBED. *Ad Hoc Networking Workshop (Med-Hoc-Net), 2011 The 10th IFIP Annual Mediterranean*. IEEE. 2011. ISBN 1457708981. 171–178.

111. Farooq, M. O. and Kunz, T. Wireless sensor networks testbeds and state-of-the-art multimedia sensor nodes. *Appl. Math. Inf. Sci*, 2014. 8: 935–940.

112. Chatzigiannakis, I., Fischer, S., Koninis, C., Mylonas, G. and Pfisterer, D. WISEBED: an open large-scale wireless sensor network testbed. In: *Sensor Applications, Experimentation, and Logistics*. Springer. 68–87. 2010. ISBN 3642118690.

113. Lim, R., Ferrari, F., Zimmerling, M., Walser, C., Sommer, P. and Beutel, J. FlockLab: A testbed for distributed, synchronized tracing and profiling of wireless embedded systems. *Proceedings of the 12th international conference on Information processing in sensor networks*. ACM. 2013. ISBN 1450319599. 153–166.

114. Gutiérrez, V., Galache, J. A., Sánchez, L., Muñoz, L., Hernández-Muñoz, J. M., Fernandes, J. and Presser, M. *SmartSantander: Internet of Things Research and Innovation through Citizen Participation*. Springer. 2013. ISBN 3642380816.

115. Sanchez, L., Galache, J. A., Gutiérrez, V., Hernández, J. M., Bernat, J., Gluhak, A. and García, T. SmartSantander: The meeting point between Future Internet research and experimentation and the smart cities. *Future Network & Mobile Summit (FutureNetw), 2011*. IEEE. 2011. ISBN 1457709287. 1–8.

116. Gavras, A., Karila, A., Fdida, S., May, M. and Potts, M. Future internet research and experimentation: the FIRE initiative. *ACM SIGCOMM Computer Communication Review*, 2007. 37(3): 89–92.

117. *FIRE FOR FUTURE INTERNET SUCCESS 2014*, 2009 (Accessed October 20, 2014). URL `http://www.ictfire.eu/fileadmin/publications/FIRE2014_iBook.pdf`.

118. Fdida, S., Friedman, T. and Parmentelat, T. OneLab: An open federated facility for experimentally driven future internet research. In: *New Network Architectures*. Springer. 141–152. 2010. ISBN 3642132464.

119. Kavoussanakis, K., Hume, A., Martrat, J., Ragusa, C., Gienger, M., Campowsky, K., Seghbroeck, G. V., Vázquez, C., Velayos, C. and Gittler, F. BonFIRE: the clouds and services testbed. *Cloud Computing Technology and Science (CloudCom), 2013 IEEE 5th International Conference on*. IEEE. 2013, vol. 2. 321–326.

120. García-Pérez, D., del Castillo, J. A. L., Al-Hazmi, Y., Martrat, J., Kavoussanakis, K., Hume, A. C., López, C. V., Landi, G., Wauters, T. and Gienger, M. Cloud and Network facilities federation in BonFIRE. *Euro-Par 2013: Parallel Processing Workshops*. Springer. 2014. ISBN 3642544193. 126–135.

121. Handziski, V., Köpke, A., Willig, A. and Wolisz, A. Twist: a scalable and reconfigurable testbed for wireless indoor experiments with sensor networks. *Proceedings of the 2nd international workshop on Multi-hop ad hoc networks: from theory to reality*. ACM. 2006. 63–70.

122. Smart Fire project. KAIST University . Avaliable online: http://eukorea-fire.eu/smartfire-testbeds/ (accessed 26 October 2014).

123. Günes, M., Blywis, B., Juraschek, F. and Schmidt, P. Concept and design of the hybrid distributed embedded systems testbed. *Freie Universität Berlin, Tech. Rep. TR-B-08-10*, 2008.

124. *Wisebed project. Braunschweig Institute of Technology. Avaliable online: http://www.wisebed.eu/#testbeds_tubs (last accessed 26 October 2014).*

125. Wisebed project. Research Academic Computer Technology Institute . Avaliable online: http://www.wisebed.eu/#testbeds_cti (last accessed 26 October 2014).

126. Wisebed project. Universitat Politecnica de Catalunya . Avaliable online: http://www.wisebed.eu/#testbeds_upc (last accessed 26 October 2014).

127. Wisebed project. Universität Bern . Avaliable online: http://www.wisebed.eu/#testbeds_ubern (last accessed 26 October 2014).

128. Wisebed project. University of Geneva . Avaliable online: http://tcslab.unige.ch/ (last accessed 26 October 2014).

129. Wisebed project. University of Geneva . Avaliable online: http://www.wisebed.eu/#testbeds_unige (last accessed 26 October 2014).

130. Guo, C., Prasad, R. V., He, J. J., Jacobsson, M. and Niemegeers, I. G. M. M. Designing a flexible and low cost testbed for Wireless Sensor Networks. *International Journal of Ad Hoc and Ubiquitous Computing*, 2012. 9(2): 111–121.

131. Delft University of Technology . Avaliable online: http://www.wisebed.eu/#testbeds_tud(last (accessed 26 October 2014).

132. Wisebed project. Lancaster University . Avaliable online: http://www.wisebed.eu/#testbeds_ulanc (last accessed 26 October 2014).

133. Lambrou, T. P. and Panayiotou, C. G. A testbed for coverage control using mixed wireless sensor networks. *Journal of Network and Computer Applications*, 2012. 35(2): 527–537.

134. Giatsios, D., Choumas, K., Syrivelis, D., Korakis, T. and Tassiulas, L. Integrating FlowVisor Access Control in a Publicly Available OpenFlow Testbed with Slicing Support. In: *Testbeds and Research Infrastructure. Development of Networks and Communities*. Springer. 387–389. 2012. ISBN 3642355757.

135. Passas, V., Chounos, K., Keranidis, S., Liu, W., Hollevoet, L., Korakis, T., Koutsopoulos, I., Moerman, I. and Tassiulas, L. Online evaluation of sensing characteristics for radio platforms in the CREW federated testbed. *Proceedings of the 19th annual international conference on Mobile computing & networking*. ACM. 2013. ISBN 1450319998. 167–170.

136. FURE project. University of Thessaly . Avaliable online: http://eukorea-fire.eu/smartfire-testbeds/(last (Accessed 26 October 2014).

137. Washington University. Avaliable online: http://wsn.cse.wustl.edu/index.php/The_WUSTL_Wireless_Sensor_Network_Testbed (accessed 26 October 2014).

138. National University of Singapore. Avaliable online: http://indriya.comp.nus.edu.sg/motelab/html/index.php (accessed 26 October 2014).

139. Doddavenkatappa, M., Chan, M. C. and Ananda, A. L. Indriya: A low-cost, 3D wireless sensor network testbed. In: *Testbeds and Research Infrastructure. Development of Networks and Communities*. Springer. 302–316. 2012. ISBN 3642292720.

140. Hurni, P., Anwander, M., Wagenknecht, G., Staub, T. and Braun, T. TARWIS: a testbed management architecture for wireless sensor network testbeds. *Proceedings of the 7th International Conference on Network and Services*

Management. International Federation for Information Processing. 2011. ISBN 3901882448. 320–323.

141. Xiao, Y., Chen, H. and Li, F. H. *Handbook on Sensor Networks*. World Scientific. 2010. ISBN 9812837302.

142. Souto, E., Guimarães, G., Vasconcelos, G., Vieira, M., Rosa, N. and Ferraz, C. A message-oriented middleware for sensor networks. *Proceedings of the 2nd workshop on Middleware for pervasive and ad-hoc computing*. ACM. 2004. ISBN 1581139519. 127–134.

143. Hong, Y. A Resource-Oriented Middleware Framework for Heterogeneous Internet of Things. *Cloud and Service Computing (CSC), 2012 International Conference on*. IEEE. 2012. ISBN 1467347248. 12–16.

144. Hoebeke, J., De Poorter, E., Bouckaert, S., Moerman, I. and Demeester, P. Managed ecosystems of networked objects. *Wireless Personal Communications*, 2011. 58(1): 125–143.

145. Lee, J.-S., Su, Y.-W. and Shen, C.-C. A comparative study of wireless protocols: Bluetooth, UWB, ZigBee, and Wi-Fi. *Industrial Electronics Society, 2007. IECON 2007. 33rd Annual Conference of the IEEE*. IEEE. 2007. ISBN 1424407834. 46–51.

146. Sayuti, H., Rashid, R. A., Mu'azzah, A. L., Hamid, A., Fisal, N., Sarijari, M., Mohd, A., Yusof, K. M. and Rahim, R. A. Lightweight priority scheduling scheme for smart home and ambient assisted living system. *International Journal of Digital Information and Wireless Communications (IJDIWC)*, 2014. 4(1): 114–123.

147. Rashid, R. A., Fisal, N. and Hamid, A. H. A. Wireless multimedia sensor network platform for low rate image/video streaming. *Jurnal Teknologi*, 2012. 54(1): 231–254.