Survey of Operating Systems for the IoT Environment

Tuhin Borgohain*
Department of Instrumentation Engineering, Assam Engineering College, Guwahati, India
Email: borgohain.tuhin@gmail.com
Uday Kumar
Tech Mahindra Limited, Chennai, India
Email: udaykumar@techmahindra.com
Sugata Sanyal
Corporate Technology Office, Tata Consultancy Services, Mumbai, India
Email: sugata.sanyal@tcs.com
**Corresponding Author*

ABSTRACT

This paper is a comprehensive survey of the various operating systems available for the Internet of Things environment. At first the paper introduces the various aspects of the operating systems designed for the IoT environment where resource constraint poses a huge problem for the operation of the general OS designed for the various computing devices. The latter part of the paper describes the various OS available for the resource constraint IoT environment along with the various platforms each OS supports, the software development kits available for the development of applications in the respective OS'es along with the various protocols implemented in these OS'es for the purpose of communication and networking.

Keywords – **IDE, IP, SDK, WSN, IoT.**

Paper submitted: Date, Revised: Date (only if applicable), Accepted: Date

I. Introduction

The whole Internet of Things environment is based on the application of microprocessors and wireless sensors. The resource constraint environment of these microprocessors and sensors makes the use of regular OS'es meaningless due to their high resource and computing power requirement. Thus, in such a situation, the development of OS'es meeting the resource constraint demand of the IoT environment becomes necessary.

II. Overview

In section III the paper introduces the various aspects of an OS designed for the IoT environment. In section IV, the various OS'es available for running in the IoT environment along with a list of the supporting platforms, SDKs and the various networking and communication protocols implemented are surveyed. The paper is concluded in section V.

III. Introduction to OS for the IoT Environment

The whole integration of the various IoT devices to the various objects is made possible through the interaction of software at a dynamic level along with the use of wireless sensor network and RFID technologies using the internet infrastructure ([1], [6]). This software interaction is made possible through the operating system running behind the scene within each IoT device without which an IoT device would be nothing more than a non-functioning device. The flexible features of the various operating systems of an IoT device has facilitated some interesting integration of electronic products and technologies to the daily processes of an individual thus making the processes a whole lot easier to use and access. Some out of the multitudes of IoT technology integration and innovations are smart light bulb ([28]), implementation of real time passenger information system ([22]), smart tags/NFC tags ([17]) etc.

The OS'es developed for the IoT environment require very few kilobytes of RAM as well as operate with low power consumption. Moreover they are specifically designed and optimized for a particular set of microprocessor-based platforms beyond which such OS'es becomes irrelevant in its application ([38]). These OS'es do not compromise in terms of features relating to communication, networking, security etc. as compared to the regular OS'es like Windows OS, Mac OS etc. but comes built-in with a number of pre-installed, pre-integrated applications, drivers and other network protocols. Moreover these OS'es employ a number of unique security measures for enhancing the IoT infrastructure as a whole and to avoid the compromise of the stability and usability of the OS.

Though the security issues of the OS'es for the IoT environment are quite different in comparison to the security issues of a regular operating system, yet it still retains the standard security protocols for protecting itself against unwanted attacks. Now the IoT environment is made in such a way so as to carry out information exchange between the various electronic devices over the internet in the most efficient way possible using the lowest amount of resources. As such the whole IoT environment along with its OS becomes prone to malicious attack from the third party intruders. So the successful implementation of various encryption and data hiding techniques ([4], [5], [12], [15], [39]), intrusion detection systems ([16], [33]) etc. in the IoT infrastructure takes a paramount importance. [45] takes care of sleep deprivation attack blockage on IoT elements, to preserve their already fragile power resources.

IV. OS'ES

i. mbed: Developed by ARM in collaboration with its technological partners, mbed OS is developed for 32-bit ARM Cortex-M microcontrollers ([29]). The whole OS is written using C and C++ language. This open source OS is licensed under Apache License 2.0.

The software development kit (SDK) for mbed OS provides the software framework for the developers to develop various microcontroller firmwares to be run on IoT devices. These SDK is comprised of core libraries which consist of the following components given in Table 1:

Networking	Test scripts	Microcontroller peripheral drivers	RTOS and runtime environment	Build Tools	Debug Scripts

Table 1: Core libraries in mbed OS

The applications for mbed OS can only be developed online using its native online code editor cum compiler known as mbed online integrated development environments (IDEs). While writing of code can only be done through a web browser, its compilation is done by the ARMCC C/C++ compiler in the cloud.

In the connectivity front, the mbed OS support the following connectivity technologies given in Table 2:

Bluetooth Low Energy	Wi-fi	Zigbee IP	Zigbee LAN
Cellular	Ethernet	6LoWPAN	

Table 2: Connectivity technologies in mbed OS

mbed OS integrates end-to-end IP security (IPv4 and IPv6) through TLS and DTLS in its comm. channels for increased security of the whole OS environment. Moreover for management of various devices in its environment, mbed OS uses OMA Lightweight M2M protocol.

ii. RIOT: Developed by INRIA, HAW Hamburg and FU Berlin initially, RIOT OS is compatible with ARM Cortex-M3, ARM Cortex-M4, ARM7, AVR Atmega and TI MSP430 devices ([8], [24], [31]). Developed using C and C++, this open source OS is licensed under LGPL v2.1.

The SDKs available for development of applications in RIOT OS are gcc, valgrind and gdb. Moreover the SDK framework supports application programming in C and C++.

RIOT OS supports all the major communication and networking protocols which are tabulated in Table 3:

IPv6	6LoWPAN	RPL	CoAP
UDP	TCP	CBOR	CCN-lite
OpenWSN		UBJSON	

Table 3: Networking protocols in RIOT OS

iii. Contiki: Created by Adam Dunkels and further developed by people from various organisations and institutions like Atmel, Cisco, ENEA, SAP, Sensinode, Oxford University etc. ([3], [19], [35]), the Contiki OS is aimed to be used in various microcontroller devices which are tabulated in Table 4:

Atmel ARM	Atmel AVR	STM32w	TI MSP430
TI CC2430	TI CC2538	TI CC2630	TI CC2650
LPC2103	Freescale MC13224	Microchip dsPIC	Microchip PIC32

Table 4: Microcontroller devices running on Contiki OS

This open source OS is licensed under BSD License.

The programming model of the Contiki OS is based on protothreads for efficient operation in resource-constrained environment.

The Contiki OS features Cooja, a network simulator which simulates Contiki nodes ([18]). These Contiki nodes are of three types:

a. Emulated nodes
b. Cooja nodes
c. Java nodes

The various networking protocols supported by Contiki OS are given in Table 5:

CoAP	6LoWPAN	RPL

Table 5: Networking protocols in Contiki OS

The Contiki environment is generally made secure through the implementation of ContikiSec ([21]) and through the implementation of TLS/DTLS ([9]).

iv. TinyOS: Developed by TinyOS Alliance, this open source OS is mainly developed for wireless sensor networks ([2], [7]). It is written in nesC and is licensed under BSD License.

The SDK for application development for TinyOS is comprised of the following three IDEs:

a. TinyDT
b. TinyOS Eclipse Plugin "YETI 2"
c. TinyOS Eclipse Editor Plugin

The various communications and network protocols implemented in the TinyOS are given in Table 5:

Broadcast based Routing	Probabilistic Routing	Multi-Path Routing
Geographical Routing	Reliability based Routing	TDMA based Routing
Directed Diffusion		

Table 5: Communication and networking protocols in TinyOS

The whole architecture of the TinyOS has been made secure over the years with the implementation of TinySec ([44]) and various types of embedded security layers ([13], [14], [30], [40]).

v. Nano-RK: Developed at Carnegie Mellon University by Alexei Colin, Christopher Palmer and Artur Balanuta, Nano-RK is specifically targeted for running in microcontrollers (presently runs on MicaZ motes and FireFly Sensor Networking Platform) to be used in wireless sensor networks. Nano-RK OS is written in C language and is open source ([10], [43]).

The application development of Nano-RK OS is supported by the Eclipse IDE.

The communications within the OS is carried out with the help of the following protocols given in Table 6:

RT-Link	PCF TDMA	b-mac	U-Connect	WiDom

Table 6: Communication protocols implemented in Nano-RK

vi. FreeRTOS: Developed by Real Time Engineers Ltd., the FreeRTOS is developed for platforms listed in Table 7:

ARM7	ARM9	ARM Cortex-M3	ARM Cortex-M4
ARM Cortex-A	RM4x	TMS570	Cortex-R4
Atmel AVR	AVR32	HCS12	Altera Nios II
MicroBlaze	Cortus APS1	Cortus APS3	Cortus APS3R
Cortus APS5	Cortus FPF3	Cortus FPS6	Cortus FPS8
Fujitsu MB91460 series	Fujitsu MB96340 series	Coldfire	V850
78K0R	Renesas H8/S	MSP430	8052
X86	RX	SuperH	PIC
Atmel SAM3	Atmel SAM4	Atmel SAM7	Atmel SAM9

Table 7: Platforms supporting FreeRTOS

Written mostly in C with the addition of a few assembly functions, this open source OS is licensed under Modified GPL ([25], [26]).

The application development part for FreeRTOS is handled through multiple threads, software timers and semaphores along with a tick-less mode for low consumption of resources by the running of the various applications.

V. CONCLUSION

From the above survey it can be seen that all the OS'es for the IoT environment are well equipped with all the major networking and communication protocols, security features as well as optimized for efficient usage of computing power in a resource constraint environment. Yet the additional implementation of counter measures to online dictionary attacks ([11], [20], [32]) in the internet infrastructure used by the IoT environment with the additional emphasis on developing a more robust wireless sensor network ([27], [34], [37], [41]) will contribute to the protection of user's credentials during online transactions ([23], [36], [42]) logging inside one's personal account in the cloud and will make the whole IoT environment much secure and more reliable.

REFERENCES

[1] Hermann Kopetz. "Internet of things." In Real-time systems, pp. 307-323. Springer US, 2011.

[2] http://en.wikipedia.org/wiki/TinyOS

[3] Adam Dunkels, Oliver Schmidt, Niclas Finne, Joakim Eriksson, Fredrik Österlind, Nicolas Tsiftes and Mathilde Durvy. "The Contiki OS: The Operating System for the Internet of Things." (2011).

[4] Sandipan Dey, Ajith Abraham, and Sugata Sanyal. "An LSB Data Hiding Technique Using Natural Number Decomposition." In *Intelligent Information Hiding and Multimedia Signal Processing, 2007. IIHMSP 2007. Third International Conference on*, vol. 2, pp. 473-476. IEEE, 2007.

[5] Philip P. Dang, Paul M. Chau. "Image encryption for secure internet multimedia applications." *Consumer Electronics, IEEE Transactions on* 46, no. 3 (2000): 395-403.

[6] Jayavardhana Gubbi, Rajkumar Buyya, Slaven Marusic and Marimuthu Palaniswami. "Internet of Things (IoT): A vision, architectural elements, and future directions." *Future Generation Computer Systems* 29, no. 7 (2013): 1645-1660.

[7] Philip Levis, Sam Madden, Joseph Polastre, Robert Szewczyk, Kamin Whitehouse, Alec Woo, David Gay, Jason Hill, Matt Welsh, Eric Brewer and David Culler. "TinyOS: An operating system for sensor networks." In *Ambient intelligence*, pp. 115-148. Springer Berlin Heidelberg, 2005.

[8] https://github.com/RIOT-OS/RIOT

[9] Vladislav Perelman. "Security in IPv6-enabled wireless sensor networks: An implementation of TLS/DTLS for the Contiki operating system." PhD diss., MSc Thesis, Jacobs University Bremen, 2012.

[10] http://www.nanork.org/projects/nanork/wiki

[11] Vipul Goyal, Virendra Kumar, Mayank Singh, Ajith Abraham, and Sugata Sanyal. "A new protocol to counter online dictionary attacks" *Computers & Security*, 25, no. 2 (2006): 114-120.

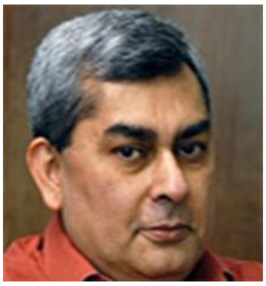
[12] Chi-Kwong Chan, Lee-Ming Cheng. "Hiding data in images by simple LSB substitution." *Pattern recognition* 37, no. 3 (2004): 469-474.
[13] David J. Malan, Matt Welsh, and Michael D. Smith. "A public-key infrastructure for key distribution in TinyOS based on elliptic curve cryptography." In *Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004. 2004 First Annual IEEE Communications Society Conference on*, pp. 71-80. IEEE, 2004.
[14] Arijit Ukil, Jaydip Sen, and Sripad Koilakonda. "Embedded security for Internet of Things." In *Emerging Trends and Applications in Computer Science (NCETACS), 2011 2nd National Conference on*, pp. 1-6. IEEE, 2011.
[15] A. V. N. Krishna, S. N. N. Pandit, and A. Vinaya Babu. "A generalized scheme for data encryption technique using a randomized matrix key." *Journal of Discrete Mathematical Sciences and Cryptography* 10, no. 1 (2007): 73-81.
[16] Animesh Kr Trivedi, Rajan Arora, Rishi Kapoor, Sudip Sanyal, and Sugata Sanyal. "A Semi-distributed Reputation Based Intrusion Detection System for Mobile Adhoc Networks." *arXiv preprint arXiv: 1006.1956* (2010).
[17] Jeffrey C. Reynar, and Ziyi Wang. "System and method for incorporating smart tags in online content." U.S. Patent 7,003,522, issued February 21, 2006.
[18] Anuj Sehgal. "Using the Contiki Cooja Simulator." (2013).
[19] Adam Dunkels, Bjorn Gronvall, and Thiemo Voigt. "Contiki- a lightweight and flexible operating system for tiny networked sensors." In *Local Computer Networks, 2004. 29th Annual IEEE International Conference on*, pp. 455-462. IEEE, 2004.
[20] Benny Pinkas, and Tomas Sander. "Securing passwords against dictionary attacks." In *Proceedings of the 9th ACM conference on Computer and communications security*, pp. 161-170. ACM, 2002.
[21] Lander Casado, and Philippas Tsigas. "Contikisec: A secure network layer for wireless sensor networks under the contiki operating system." In *Identity and Privacy in the Internet Age*, pp. 133-147. Springer Berlin Heidelberg, 2009.
[22] K. Ganesh, M. Thrivikraman, Joy Kuri, Haresh Dagale, G. Sudhakar, and Sugata Sanyal. "Implementation of a real time passenger information system." *arXiv preprint arXiv: 1206.0447* (2012).
[23] Alain Hiltgen, Thorsten Kramp, and Thomas Weigold. "Secure internet banking authentication." *Security & Privacy, IEEE* 4, no. 2 (2006): 21-29.
[24] Emmanuel Baccelli, Oliver Hahm, M. Gunes, M. Wahlisch, and Thomas C. Schmidt. "RIOT OS: Towards an OS for the Internet of Things." In *Computer Communications Workshops (INFOCOM WKSHPS), 2013 IEEE Conference on*, pp. 79-80. IEEE, 2013.
[25] http://en.wikipedia.org/wiki/FreeRTOS
[26] http://www.freertos.org/
[27] Koustubh Kulkarni, Sudip Sanyal, Hameed Al-Qaheri, and Sugata Sanyal. "Dynamic Reconfiguration of Wireless Sensor Networks." *IJCSA* 6, no. 4 (2009): 16-42.
[28] Ihor Lys, and George G. Mueller. "Smart light bulb." U.S. Patent 6,528,954, issued March 4, 2003.
[29] https://mbed.org/technology/os/
[30] Sachin Babar, Antonietta Stango, Neeli Prasad, Jaydip Sen, and Ramjee Prasad. "Proposed embedded security framework for internet of things (IoT)." In *Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology (Wireless VITAE), 2011 2nd International Conference on*, pp. 1-5. IEEE, 2011.
[31] http://www.riot-os.org/
[32] Yongzhong He, and Zhen Han. "User authentication with provable security against online dictionary attacks." *Journal of Networks* 4, no. 3 (2009): 200-207.
[33] Manoj Rameshchandra Thakur, and Sugata Sanyal. "A Multi-Dimensional approach towards Intrusion Detection System." *arXiv preprint arXiv: 1205.2340*(2012).
[34] Javier López, and Jianying Zhou, eds. *Wireless sensor network security*. Vol. 1. IOS Press, 2008.
[35] http://www.contiki-os.org/
[36] Yuri Khidekel, Alex Balashov, and Vladimir Bashmakov. "Secure transaction system." U.S. Patent Application 09/792,391, filed February 23, 2001.
[37] Mingbo Xiao, Xudong Wang, and Guangsong Yang. "Cross-layer design for the security of wireless sensor networks." In *Intelligent Control and Automation, 2006. WCICA 2006. The Sixth World Congress on*, vol. 1, pp. 104-108. IEEE, 2006. Liu, An, Mihui Kim, Leonardo B. Oliveira, and Hailun Tan. "Wireless Sensor Network Security." *International Journal of Distributed Sensor Networks* 2013 (2013).
[38] http://micrium.com/iot/iot-rtos/
[39] Harshavardhan Kayarkar, and Sugata Sanyal. "A survey on various data hiding techniques and their comparative analysis." *arXiv preprint arXiv: 1206.1957*(2012).
[40] Kresimir Grgic, Drago Zagar, and Visnja Krizanovic. "Security in IPv6-based wireless sensor network—Precision agriculture example." In *Telecommunications (ConTEL), 2013 12th International Conference on*, pp. 79-86. IEEE, 2013.
[41] Adrian Perrig, John Stankovic, and David Wagner. "Security in wireless sensor networks." *Communications of the ACM* 47, no. 6 (2004): 53-57.
[42] Sugata Sanyal, Ayu Tiwari, and Sudip Sanyal. "A multifactor secure authentication system for wireless payment." In *Emergent Web Intelligence: Advanced Information Retrieval*, pp. 341-369. Springer London, 2010.
[43] Anand Eswaran, Anthony Rowe, and Raj Rajkumar. "Nano-rk: an energy-aware resource-centric rtos for sensor

networks." In *Real-Time Systems Symposium, 2005. RTSS 2005. 26th IEEE International*, pp. 10-pp. IEEE, 2005.
[44] Chris Karlof, Naveen Sastry, and David Wagner. "TinySec: a link layer security architecture for wireless sensor networks." In *Proceedings of the 2nd international conference on Embedded networked sensor systems*, pp. 162-175. ACM, 2004.
[45] Tapalina Bhattasali, Rituparna Chaki, Sugata Sanyal; "Sleep Deprivation Attack in Wireless Sensor Network": International Journal of Computer Applications, Volume 40,Number 15, pp.19-25, February 2012, ISBN: 978-93-80866-55-8, Published by Foundation of Computer Science, New York, USA, DOI: 10.5120/5056-7374.

Biographies and Photographs

Tuhin Borgohain is a 3rd Year student of Assam Engineering College, Guwahati. He is presently pursuing his Bachelor of Engineering degree in the department of Instrumentation Engineering.

Uday Kumar is working as Delivery Manager at Tech Mahindra Ltd, India. He has 17 years of experience in engineering large complex software system for customers like Citibank, FIFA, Apple Smart objects and AT&T. He has developed products in BI, performance testing, compilers. And have successfully led projects in finance, content management and ecommerce domain. He has participated in many campus connect program and conducted workshop on software security, skills improvement for industrial strength programming, evangelizing tools and methodology for secure and high end programming.



Sugata Sanyal is presently acting as a Research Advisor to the Corporate Technology Office, Tata Consultancy Services, India. He was with the Tata Institute of Fundamental Research till July, 2012. Prof. Sanyal is a: Distinguished Scientific Consultant to the International Research Group: Study of Intelligence of Biological and Artificial Complex System, Bucharest, Romania; Member, "Brain Trust," an advisory group to faculty members at the School of Computing and Informatics, University of Louisiana at Lafayette's Ray P. Authement College of Sciences, USA; an honorary professor in IIT Guwahati and Member, Senate, Indian Institute of Guwahati, India. Prof. Sanyal has published many research papers in international journals and in International Conferences worldwide: topics ranging from network security to intrusion detection system and more.