A Dissertation submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

New Information Model that Allows Logical Distribution of the Control Plane for Software-Defined Networking

The Distributed Active Information Model (DAIM) can enable an effective distributed control plane for SDN with OpenFlow as the standard protocol

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I dedicate this thesis to my lovely father, mother, sister, beloved wife and sons for their love and support.

CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Abstract

In recent years, technological innovations in communication networks, computing applications and information modelling have been increasing significantly in complexity and functionality driven by the needs of the modern world. As large-scale networks are becoming more complex and difficult to manage, traditional network management paradigms struggle to cope with traffic bottlenecks of the traditional switch and routing based networking deployments. Recently, there has been a growing movement led by both industry and academia aiming to develop mechanisms to reach a management paradigm that separates the control plane from the data plane.

A new emerging network management paradigm called Software-Defined Networking (SDN) is an attempt to overcome the bottlenecks of traditional data networks. SDN offers a great potential to ease network management, and the OpenFlow protocol in particularly often referred to a radical new idea in networking. SDN adopts the concept of programmable networks which separate the control decisions from forwarding hardware and thus enabling the creation of a standardised programming interface. Flow computation is managed by a centralised controller with the switches only performing simple forwarding functions. This allows researchers to implement their protocols and algorithms to control data packets without impacting on the production network. Therefore, the emerging OpenFlow technology provides more flexible control of networks infrastructure, are cost effective, open and programmable components of network architecture.

SDN is very efficient at moving the computational load away from the forwarding plane and into a centralised controller, but a physically centralised controller can represent a single point of failure for the entire network. This centralisation approach brings optimality, however, it creates additional problems of its own including single-domain restriction, scalability, robustness and the ability for switches to adapt well to changes in local environments.

This research aims at developing a new distributed active information model (DAIM) to allow programmability of network elements and local decision-making processes that will essentially contribute to complex distributed networks. DAIM offers adaptation algorithms embedded with intelligent information objects to be applied to such complex systems. By applying the DAIM model and these adaptation algorithms, managing complex systems in any distributed network environment can become scalable, adaptable and robust. The DAIM model is integrated into the SDN architecture at the level of switches to provide a logically distributed control plane that can manage the flow setups. The proposal moves the computational load to the

switches, which allows them to adapt dynamically according to real-time demands and needs. The DAIM model can enhance information objects and network devices to make their local decisions through its active performance, and thus significantly reduce the workload of a centralised SDN/OpenFlow controller.

In addition to the introduction (Chapter 1) and the comprehensive literature reviews (Chapter 2), the first part of this dissertation (Chapter 3) presents the theoretical foundation for the rest of the dissertation. This foundation is comprised of the logically distributed control plane for SDN networks, an efficient DAIM model framework inspired by the O:MIB and *hybrid O:XML* semantics, as well as the necessary architecture to aggregate the distribution of network information. The details of the DAIM model including design, structure and packet forwarding process are also described.

The DAIM software specification and its implementation are demonstrated in the second part of the thesis (Chapter 4). The DAIM model is developed in the C++ programming language using free and open source NetBeans IDE. In more detail, the three core modules that construct the DAIM ecosystem are discussed with some sample code reviews and flowchart diagrams of the implemented algorithms. To show DAIM's feasibility, a small-size OpenFlow lab based on Raspberry Pi's has been set up physically to check the compliance of the system with its purpose and functions. Various tasks and scenarios are demonstrated to verify the functionalities of DAIM such as executing a ping command, streaming media and transferring files between hosts. These scenarios are created based on OpenVswitch in a virtualised network using *Mininet*.

The third part (Chapter 5) presents the performance evaluation of the DAIM model, which is defined by four characteristics: round-trip-time, throughput, latency and bandwidth. The ping command is used to measure the mean RTT between two IP hosts. The flow setup throughput and latency of the DAIM controller are measured by using *Cbench*. Also, *Iperf* is the tool used to measure the available bandwidth of the network. The performance of the distributed DAIM model has been tested and good results are reported when compared with current OpenFlow controllers including NOX, POX and NOX-MT. The comparisons reveal that DAIM can outperform both NOX and POX controllers. The DAIM's performance in a physical OpenFlow test lab and other parameters that can affect the performance evaluation are also discussed.

Because decentralisation is an essential element of autonomic systems, building a distributed computing environment by DAIM can consequently enable the development of autonomic management strategies. The experiment results show the DAIM model can be one of the architectural approaches to creating the autonomic service management for SDN. The DAIM model can be utilised to investigate the functionalities required by the autonomic networking within the ACNs community. This efficient DAIM model can be further applied to enable adaptability and autonomy to other distributed networks such as WSNs, P2P and Ad-Hoc sensor networks.

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Nomenclature

AA	Autonomous Agent
ACNs	Autonomic Communication Networks
ACs	Autonomic Communications
ADSs	Autonomous Decentralised Systems
API	Application Programming Interface
ASIC	Application-Specific Integrated Circuit
BGP	Border Gateway Protocol
CLI	Command Line Interface
DAI	Distributed Artificial Intelligent
DAIM	Distributed Active Information Model
DHCP	Dynamic Host Configuration Protocol
DMI	Desktop Management Interface
DMTF	Distributed Management Task Force
DNS	Domain Name System
FCAPS	fault, configuration, accounting, performance, security
FTP	File Transfer Protocol
IETF	Internet Engineering Task Force
ISO	International Organization for Standardization
LLDP	Link Layer Discovery Protocol
LTE	Long Term Evolution
MANET	Mobile Ad hoc Network

MEs	Managed Elements
MIB	Management Information Base
NETCONF	Network Configuration Protocol
NFV	Network Functions Virtualisation
NGN	Next Generation Network
NIB	Network Information Base
NOS	Network Operating System
OFLOPS	OpenFlow Operations Per Second
OSCA	Operating System Communication Application
OSPF	Open Shortest Path First
OSS	Operations Support System
OVSDB	OpenvSwitch Database Management Protocol
QoS	Quality of Service
RESTful	Representational State Transfer
RNC	Radio Network Controllers
SDN	Software-Defined Networking
SID	Shared Information and Data Model
SLAs	Service Level Agreements
SOAP	Simple Object Access Protocol
SSL	Secure Sockets Layer
STP	Spanning Tree Protocol
TLS	Transport Layer Security
TMF	TeleManagement Forum
UML	Unified Modelling Language
VETH	Virtual Ethernet

VMs	Virtual Machines
WASNs	Wireless Ad-hoc Sensor Networks
WiMAX	Worldwide Interoperability for Microwave Access
WSN	Wireless Sensor Network
XACML	eXtended Access Control Markup Language
XML	Extensible Markup Language
XML-RPC	XML-encode Remote Procedure Call

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Related Publications

The technical contributions and discussions in the thesis are mainly based on the following publications written by the author in which five of them are co-authored:

A. International Journal Publications:

[J1] Pupatwibul, Pakawat, Ameen Banjar, Abdallah AL Sabbagh, and Robin Braun. "A Comparative Review: Accurate OpenFlow Simulation Tools for Prototyping." Journal of Networks 10, no. 5 (2015): 322-327.

[J2] Banjar Ameen, Pakawat Pupatwibul, and Robin Braun. "DAIM: A Mechanism to Distribute Control Functions Within OpenFlow Switches." Journal of Networks 9.1 (2014): 1-9.

[J3] Banjar Ameen, Pakawat Pupatwibul, Abdallah AL Sabbagh, and Robin Braun. "Using an ICN Approach to Support Multiple Controllers in OpenFlow." International Journal of Electrical & Computer Sciences 14, no. 2 (2014).

B. International Conference Publications:

[C1] Pupatwibul, Pakawat, Ameen Banjar, and Robin Braun. "Using DAIM as a Reactive Interpreter for OpenFlow Networks to Enable Autonomic Functionality." ACM SIGCOMM Computer Communication Review. Vol. 43. No. 4. ACM, 2013.

[C2] Pupatwibul, P., Jozi, B. and Braun, R. 2011, "Investigating O:MIB-Based Distributed Active Information Model (DAIM) for Autonomics", International Conference on Information and Communication Technologies and Applications IIIS, Orlando, Florida, USA, pp. 7-12.

[C3] Pupatwibul, P., Sabbagh, A.A.L., Banjar, A. & Braun, R. 2012, "Distributed Systems in Next Generation Networks", 1st Australian Conference on the Applications of Systems Engineering ACASE'12, p. 32.

[C4] Pupatwibul, P., Banjar, A., Al Sabbagh, A., & Braun, R. (2013, October). "Developing an Application Based on OpenFlow to Enhance Mobile IP Networks". In Local Computer Networks Workshops (LCN Workshops), 2013 IEEE 38th Conference on (pp. 936-940). IEEE.

[C5] Al Sabbagh, A., Pupatwibul, P., Banjar, A., & Braun, R. (2013, October). "Optimization of the OpenFlow Controller in Wireless Environments for Enhancing Mobility". In Local Computer Networks Workshops (LCN Workshops), 2013 IEEE 38th Conference on (pp. 930-935). IEEE

[C6] Banjar, A., Pupatwibul, P., Braun, R., & Moulton, B. (2014, February). "Analysing the Performance of the OpenFlow Standard for Software-Defined Networking Using the OMNeT++ Network Simulator". In Computer Aided System Engineering (APCASE), 2014 Asia-Pacific Conference on (pp. 31-37). IEEE.

[C7] Pupatwibul, P., Banjar, A. & Braun, R. 2014, "Performance Evaluation of TCP/IP vs. OpenFlow in INET Framework Using OMNeT++, and Implementation of Intelligent Computational Model to Provide Autonomous Behaviour." The Asian Conference on Technology, Information & Society 2014, The International Academic Forum (IAFOR) Osaka, Japan, pp. 43-56.

C. International Book Chapter Publications:

[B1] Pupatwibul, Pakawat, Ameen Banjar, Abdallah AL Sabbagh, and Robin Braun. "An Intelligent Model for Distributed Systems in Next Generation Networks." In Advanced Methods and Applications in Computational Intelligence, pp. 315-334. Springer International Publishing, 2014.

[B2] Banjar, Ameen, Pakawat Pupatwibul, and Robin Braun. "Comparison of TCP/IP Routing Versus OpenFlow Table and Implementation of Intelligent Computational Model to Provide Autonomous Behaviour." Computational Intelligence and Efficiency in Engineering Systems. Springer International Publishing, 2015. 121-142.