RGC Ref. No.:
UGC/FDS16/E05/14
(please insert ref. above)

RESEARCH GRANTS COUNCIL
COMPETITIVE RESEARCH FUNDING SCHEMES FOR THE LOCAL SELF-FINANCING DEGREE SECTOR

FACULTY DEVELOPMENT SCHEME (FDS)

Completion Report
(for completed projects only)

Submission Deadlines:	*1. Auditor's report with unspent balance, if any: within **six** months of the approved project completion date.* *2. Completion report: within **12** months of the approved project completion date.*

Part A: The Project and Investigator(s)

1. Project Title

Enabling Adaptive and Secure Cloud Connectivity for Cognitive Radio Networks

2. Investigator(s) And Academic Department(s) / Unit(s) Involved

Research Team	Name / Post	Unit / Department / Institution
Principal Investigator	WONG Kin-yeung / Associate Professor	School of Science and Technology / The Open University of Hong Kong
Co-Investigator(s)	YEUNG Kai-hau / Associate Professor	Department Electronics Engineering / City University of Hong Kong
	CHOY Sheung-on / Associate Professor	School of Science and Technology / The Open University of Hong Kong

3. Project Duration

	Original	Revised	Date of RGC / Institution Approval *(must be quoted)*
Project Start Date	1 January 2015	N.A.	
Project Completion Date	31 December 2016	N.A.	
Duration *(in month)*	24	N.A.	
Deadline for Submission of Completion Report	31 December 2017	N.A.	

Part B: The Final Report

5. Project Objectives

5.1 Objectives as per original application

1. To design an algorithm for efficient gateway placement with the consideration of a number of performance constraints (e.g., traffic demand, location proximity, and capacity fluctuation). The algorithm is able to determine the minimum number of cloud gateways needed and their placement so as to minimize the deployment cost while maintaining acceptable quality of service. To design such algorithm, solving an optimization problem will be required.

2. To design a default gateway selection algorithm for CR nodes and to select cloud gateways so that more efficient cloud connectivity can be achieved. As the network parameters are dynamic, in the design of this algorithm, we will use the collaborative feedback model that allows CR nodes to exchange information and to make gateway selection decisions.

3. To design a routing algorithm for CRNs which is able to adapt to the changing network environment of CRNs including topological changes, dynamic traffic demands, and available capacity of cloud gateway. In the design of such algorithm, Reinforcement Learning, a biologically inspired technique, will be used.

4. To design a malicious-node detection algorithm. Malicious nodes are those that disrupt cloud connectivity in CRNs by methods like redirecting packets to wrong direction or interfering with communications of the primary nodes. We will use the belief propagation (BP) model to identify the possible malicious nodes and then avoid including them in the future path discovery process.

5.2 Revised objectives

Date of approval from the RGC: N.A.

Reasons for the change: N.A.

5.3 Realisation of the objectives
(Maximum 1 page; please state how and to what extent the project objectives have been achieved; give reasons for under-achievements and outline attempts to overcome problems, if any)

As for Objective 1, we have fully realized the objective stated. We proposed a cloud gateway placement algorithm for cognitive radio networks, which could select a minimum number of gateways satisfying the interference and the traffic demand constraints. First, we formulated the gateway placement as an integer linear programming problem, with the number of gateways as the objective. Then, we proposed an effective heuristic algorithm to solve the NP-hard gateway placement problem. The heuristic algorithm recursively merges the gateways, while consistently satisfying the constraints, until no more merges could be performed. After that, the minimum number of gateways satisfying constraints is determined.

As for Objective 2, we have fully realized the objective stated. We proposed a cloud gateway management algorithm for cognitive radio networks, which could select the optimal gateway for the source to connect with the cloud. To realize that, gateway candidates are firstly grouped into different clusters based on the interference from primary users (PUs), and the dynamic link connectivity due to cognitive radio users (CUs) mobility. The gateway candidate with most stable connectivity with other cluster members would be selected as the cluster head. Therefore, stable clusters would be formed as stable backbone connecting with the cloud for cognitive radio users. After that, we introduced a hybrid Gateway Discovery/Advertisement mechanism, which allows periodical gateway advertisement within the cluster. And when a source wants to connect to the cloud, it only needs to send on-demand gateway discovery to its closest gateway candidates to get information of the cluster head. With the information collected, the source could select its optimal gateway satisfying its quality of service (QoS) constraints.

As for Objective 3, we have fully realized the objective stated. Since the link connectivity in cognitive radio networks is dynamic due to CU mobility and PU interference, link stability should be considered into route selection. We proposed link stability estimation by predicting the residual connection time of the link with consideration of CU mobility and PU interference. Then, we introduced the route stability as the minimum link stability of all the links along the route. During gateway discovery process, the path stability could also be obtained. The source could select the optimal route satisfying its QoS constraints.

As for Objective 4, we have fully achieved the objective stated. In cognitive radio networks, malicious nodes perform uncooperative behaviors. We studied the effect of different degrees of node cooperation on routing performance in cognitive radio networks. First, we proposed an analytical framework and derived the end-to-end packet delivery ratio (PDR) in the context of malicious nodes. Then, we validated our analytical model through simulations. The analytical model is helpful to understand the properties of malicious users and to design the ways to detect them. Moreover, we proposed a trust management model to identify malicious nodes in cognitive radio networks. Through monitoring forwarding behaviors of each CU, the trust value of each CU could be constructed. Then, the trust value was used as a criterion to identify malicious nodes.

5.4 Summary of objectives addressed to date

Objectives *(as per 5.1/5.2 above)*	**Addressed** *(please tick)*	**Percentage Achieved** *(please estimate)*
1. To design an algorithm for efficient gateway placement with the consideration of a number of performance constraints (e.g., traffic demand, location proximity, and capacity fluctuation). The algorithm is able to determine the minimum number of cloud gateways needed and their placement so as to minimize the deployment cost while maintaining acceptable quality of service. To design such algorithm, solving an optimization problem will be required.	✓	100%
2. To design a default gateway selection algorithm for CR nodes and to select cloud gateways so that more efficient cloud connectivity can be achieved. As the network parameters are dynamic, in the design of this algorithm, we will use the collaborative feedback model that allows CR nodes to exchange information and to make gateway selection decisions.	✓	100%
3. To design a routing algorithm for CRNs which is able to adapt to the changing network environment of CRNs including topological changes, dynamic traffic demands, and available capacity of cloud gateway. In the design of such algorithm, Reinforcement Learning, a biologically inspired technique, will be used.	✓	100%
4. To design a malicious-node detection algorithm. Malicious nodes are those that disrupt cloud connectivity in CRNs by methods like redirecting packets to wrong direction or interfering with communications of the primary nodes. We will use the belief propagation (BP) model to identify the possible malicious nodes and then avoid including them in the future path discovery process.	✓	100%

6. Research Outcome

6.1 Major findings and research outcome
(Maximum 1 page; please make reference to Part C where necessary)

We proposed a cloud gateway placement algorithm for cognitive radio networks, which could select a minimum number of gateways satisfying the interference and the traffic demand constraints. The algorithm could run in polynomial time to obtain an approximate result. And the algorithm exhibited smooth and consistent performance while fulfilling various kinds of constraints. From the simulation results, we found that our algorithm requires a less number of gateways compared with other traditional algorithms. The research outcome has been addressed in the 1st journal paper as stated in Part C-8.

We proposed a mobile cloud gateway management framework for integrating cognitive radio ad hoc networks with the cloud. We introduced the concept of mobile gateways, which are CUs satisfying the required metrics. And these mobile gateways are clustered to perform as the stable backbone connected with the cloud. A hybrid gateway discovery algorithm, and QoS-based gateway and route selection algorithm were proposed for each CU to select the optimal routing path to the optimal gateway. The mobile gateway management could achieve high average throughput, low end-to-end delay, and low packet drop fractions, compared to other gateway management method. The research outcome has been addressed in the 2nd journal paper as stated in Part C-8.

We proposed an analytical framework to study the impact of uncooperative behaviors on the routing performance in cognitive radio networks. With the framework, we derived the expected end-to-end packet delivery ratio (PDR). Extensive simulation results validated the analytical model. From the analysis, some insights of routing in cognitive radio networks can be obtained. First, the end-to-end PDR decreases rapidly as the selfish user intensity increases. Thus, selfish users should be avoided from route selection to improve PDR. Second, even a modest increment of node cooperation level is sufficient to achieve significant performance improvement in PDR. Therefore, some motivation mechanisms should be adopted in order to get better routing performance. The details of the research findings has been published in the 1st conference paper stated in Part C-9.

We proposed a trust-based routing model to defend against routing disruption attacks in cognitive radio networks. First, we constructed the trust values of CUs in cognitive radio networks by monitoring the forwarding behaviors of CUs. Then, we could identify the malicious nodes and then avoid them in route selections. The proposed routing model was effective in improving throughput and end-to-end delay through simulations. The research outcome has been published in the 2nd conference paper stated in Part C-9.

6.2 Potential for further development of the research and the proposed course of action *(Maximum half a page)*

The research outcomes of this project could be applied into real cognitive radio networks to provide efficient and secure cloud connectivity for cognitive radio users. But the real cognitive radio networks show social properties because the cognitive process of cognitive radio users is inherent in human behavior. Many social properties (e.g. community, friendship and individual selfishness) have been recently studied in cognitive radio networks. The social properties determine the contact frequency or contact duration, and hence affect the physical connections in CRNs. But how to evaluate the impact of the social properties to the performance of cloud connectivity is still unexplored for cognitive radio networks. In the future research, it is possible to utilize the analytical framework we formed in this project to analyze the impact of social properties to cloud connectivity. Then, the results obtained could be utilized to enhance cloud connectivity for cognitive radio networks.

7. Layman's Summary

(Describe in layman's language the nature, significance and value of the research project, in no more than 200 words)

Cognitive radio networks (CRNs) are promising in solving the spectrum scarcity problem by allowing cognitive radio (CR) devices to exploit spectrum channels temporally unused by their licensed users. Since CR devices are commonly equipped with limited storage and processing power, to perform more sophisticated functions, the cloud resources (storage and computation) can be utilized.

Providing connectivity to cloud is essential for the users in CRNs. However, the existing cloud connectivity in CRNs is inefficient and unsecure because the environment changes and malicious behaviors unique to CRNs are not considered.

In this project, we proposed a cloud gateway placement algorithm to give an optimal placement of gateways. Then, we designed a gateway management algorithm for CR users to select cloud gateways and choose the routing path to the gateway so that a more efficient cloud connectivity can be achieved. Finally, we proposed an algorithm to identify the malicious nodes and mitigate the effect of malicious behaviors. The algorithms proposed in this project could be applied in real CRNs. They will benefit not only network carriers but also cloud service providers and end users. It is because the network resources can be better utilized and users can experience better cloud services.

Part C: Research Output

8. Peer-Reviewed Journal Publication(s) Arising Directly From This Research Project

(Please attach a copy of the publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)

The Latest Status of Publications				Author(s)	Title and Journal / Book	Submitted to RGC	Attached to this Report	Acknowl-edged the Support of RGC	Accessible from the institutional repository
Year of Publication	**Year of Acceptance** *(For paper accepted but not yet published)*	**Under Review**	**Under Preparation** *(optional)*	**Author(s)** *(denote the correspond-ing author with an asterisk*)*	**Title and Journal / Book** *(with the volume, pages and other necessary publishing details specified)*	**Submitted to RGC** *(indicate the year ending of the relevant progress report)*	**Attached to this Report** *(Yes or No)*	**Acknowl-edged the Support of RGC** *(Yes or No)*	**Accessible from the institutional repository** *(Yes or No)*
		✓		Ling Hou, Angus K. Y. Wong*, and Alan K. H. Yeung	Gateway placement optimization in cognitive wireless mesh networks KSII Transactions on Internet and Information Systems	No	Yes (Attachment 1)	Yes	Yes
		✓		Ling Hou, Angus K. Y. Wong*, Alan K. H. Yeung, and Steven S. O. Choy	Clustering-based mobile gateway management in integrated CRAHN-cloud network KSII Transactions on Internet and Information Systems	No	Yes (Attachment 2)	Yes	Yes

9. Recognized International Conference(s) In Which Paper(s) Related To This Research Project Was / Were Delivered
(Please attach a copy of each conference abstract)

Month / Year / Place	**Title**	**Conference Name**	**Submitted to RGC** *(indicate the year ending of the relevant progress report)*	**Attached to this Report** *(Yes or No)*	**Acknowledged the Support of RGC** *(Yes or No)*	**Accessible from the institutional repository** *(Yes or No)*
02/2016/ Lisbon, Portugal	Exploring the Impact of Node Cooperation Level on Routing in Cognitive Radio Networks	The Sixth International Conference on Advances in Cognitive Radio	Yes 2016	Yes (Attachment 3)	Yes	Yes
12/2016/ Guangzhou, China	Using trust management to defend against routing disruption attacks for cognitive radio networks	2016 IEEE International Conference on Consumer Electronics-China (ICCE-China)	No	Yes (Attachment 4)	Yes	Yes

10. Whether Research Experience And New Knowledge Has Been Transferred / Has Contributed To Teaching And Learning
(Please elaborate)

The research experience has contributed to the PI's teaching in computer network related courses (e.g., Computer Networking), as it enriches the PI's knowledge in the field.

Besides, the research experience was covered in the course of Engineering Professional Practice, in which the topics of technology transfer and research methodology are covered.

On the other hand, the research work inspired a number of final year project topics that are related to cloud.

11. Student(s) Trained
(Please attach a copy of the title page of the thesis)

Name	**Degree Registered for**	**Date of Registration**	**Date of Thesis Submission / Graduation**
Nil			

12. Other impact

(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, teaching enhancement, etc.)

Nil

***13.* Public access of completion report**

(Please specify the information, if any, that cannot be provided for public access and give the reasons.)

Information that cannot be provided for public access	Reasons
Nil	