RGC Ref.: M-HKUST609/13
(please insert ref. above)

The Research Grants Council of Hong Kong
SRFDP & RGC ERG Joint Research Scheme
Completion Report

(Please attach a copy of the completion report submitted to the Ministry of Education by the Mainland researcher)

Part A: The Project and Investigator(s)

1. Project Title

Revenue Maximization for Wireless Operators in Hybrid Macrocell-Femtocell Networks
毫微微蜂窩網絡中最大化移動運營商收益的方法研究

2. Investigator(s) and Academic Department/Units Involved

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof. Qian Zhang	Prof. Tao Jiang
Post	Tencent Professor of Engineering and Chair Professor	Professor
Unit / Department / Institution	Computer Science and Engineering/ Hong Kong University of Science and Technology	Electronics and Information Engineering/ Huazhong University of Science and Technology
Contact Information	852-23588766 qianzh@cse.ust.hk	taojiang@hust.edu.cn
Co-investigator(s) *(with title and Institution)*		
PhD student(s) (with period of involvement)	Name: Wei Wang Institution: HKUST Period from 01 Jan 2014 to 1 Jan 2015 Name: Yanjiao Chen Institution: HKUST Period from 01 Jan 2014 to 30 Jan 2015 Name: Zhice Yang Institution: HKUST Period from 01 Jan 2014 to 31 Aug 2016 Name: Lin Yang Institution: HKUST	

	Period from 01 Jan 2014 to 31 Aug 2016 Qianyi Huang Institution: HKUST Period from 01 Jan 2014 to 31 Dec 2016	

Note: The Hong Kong project team must involve at least one research postgraduate student pursuing a Doctor of Philosophy degree at the UGC-funded university (PhD student) at any time throughout the project period.

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted*)
Project Start date	01/01/2014		
Project Completion date	31/12/2016		
Duration *(in month)*	36		
Deadline for Submission of Completion Report	Dec. 31, 2017		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. To motivate both network operators and femto-holders to engage in the hybrid access mode in femtocell networks by proposing a utility-aware refunding framework;
2. To improve network stability by proposing a cooperative femtocell outage detection architecture to autonomously detect femtocells that have gone out of service;
3. To control cross-tier interference by proposing an interference management framework that incorporates the concepts of spectrum allocation, power control and base station deployment, thereby guaranteeing the quality of service for both femto-users and macro-users.

5.2 Revised Objectives

Nil

6. Research Outcome

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

Through this project, we have successfully obtained the results from the following aspects.
1. Cooperative Architecture Design for Self-Organizing Femtocell Networks
1.1 By reducing the distance between base stations and end users, femtocells provide higher data rates and better indoor coverage with its small size. The management and maintenance of dense femtocell networks may require a significant amount of human involvement. The self-organizing network (SON) is believed to be the most attractive approach. In this work [J1], we discussed three possible architectures, i.e., distributed, centralized, as well as local cooperative self-healing to achieve self-healing functionality. Both advantages and limitations for each architecture have been investigated.
1.2 As an essential functionality in SON, cell outage detection is developed to autonomously detect macrocells or femtocells that are inoperative and unable to provide service. Based on the observation that spatial correlations among users can be extracted to cope with these challenges, in this work [J1 and J7] we proposed a Cooperative femtocell Outage Detection (COD) architecture, which outperforms the existing scheme in both communication overhead and detection accuracy.

1.3 Motivated by recent innovations in software-defined wireless networking (SDWN), in this project, we systematically investigated the spectrum management architecture design that reaps the benefits of SDWN while maintaining the features of fine-grained channelization [J7]. We shed light on design principles and key challenges in realizing the SDWN-enabled spectrum management architecture and develop a general architecture with a new baseband virtualization design.

2. Spectrum Market Mechanism Design for Efficient Spectrum Management

2.1 In secondary spectrum trading markets, auctions are widely used by spectrum holders (SHs) to redistribute their unused channels to secondary wireless service providers (WSPs). In this work [C1], we consider a three-layered spectrum trading market consisting of the SH, the WSPs, and the end users. For this market, we design a novel auction mechanism to enable dynamic supplies and demands in the auction and proved that it not only maximizes the social welfare but also preserves other nice properties such as truthfulness and computational tractability.

2.2 In the spectrum auction, if a buyer locates in a “critical” place, interfering with a lot of other buyers, his occupancy of the spectrum may deprive many other transmission opportunities. In this work [J2], we proposed a Location-aware Online Truthful doUble auction Scheme (LOTUS), which incorporates the buyers’ location information into auction mechanism design. The simulation results show that LOTUS outperforms the existing online auction mechanism, significantly improving buyers’ and sellers’ utility.

2.3 Auctions are among the best-known market-based tools to provide dynamic spectrum redistribution. However, the issue of privacy preservation in spectrum auctions remains open. In this project, we developed PISA [J4], which is a PrIvacy preserving and Strategy-proof Auction mechanism for spectrum allocation. PISA provides protection for both bid privacy and coverage/interference area privacy.

2.4 The spectrum regulator simply allocates the spectrum to maximize its income, but such an income-centric allocation does not ensure the best spectrum utilization by the users. This motivates us to design a new spectrum allocation scheme which jointly considers the spectrum regulator's income and the users' aggregate utility by investigating three market tiers: the spectrum regulator, 4G and Super Wi-Fi operator coalitions, and all the wireless users [J3][C3]. We prove that the proposed scheme significantly improves users' aggregate utility with a limited spectrum regulator's income loss.

3. Interference Management and Resource Management Scheme Design

3.1 In this work [C5], we presented OpenTDMF, an architecture to enable TDMA on commodity WLAN devices. OpenTDMF is inspired by and architecturally similar to Software Defined Networking (SDN). Specifically, we leveraged the backhaul of WLAN to coordinate all the stations for channel access. This fine-grained coordination is performed in a decoupled control plane which includes a central controller and programmable APs. To realize OpenTDMF on commodity WLAN devices, we developed several novel techniques to achieve us-level time synchronization among all the APs. We also enabled AP-triggered uplink transmission so that all the transmissions in the WLAN can be determined.

3.2 Fixed channelization configuration in today’s wireless devices falls inefficient in the presence of growing data traffic and heterogeneous devices. We propose SEER [C4][J8], a frame-level wideband spectrum adaptation solution which consists of: i) a specially-constructed preamble that can be detected by receivers with arbitrary RF bands, and ii) a spectrum detection algorithm that identifies the desired transmission band in the context of multiple asynchronous senders. SEER can be realized on commodity radios, and can be easily integrated into devices running different PHY/MAC protocols.

3.3 How to estimate the optimal data rate in a fluctuated channel remains of great concern. In this project [J5], we observe that by digging into both PHY layer decoder and upper layer protocol headers, more reliable data bits with high confidence level can be exploited. These data bits, termed smart pilot, can be used to calibrate the channel estimation measurements cost-efficiently. Based on the calibrated estimation, we further propose a novel greedy rate selection algorithm to track the optimal data rate, which successfully avoids the impact of deep fading subcarriers in both legacy 802.11a/g and 802.11n MIMO systems.

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

The directions explored in this project are interesting and not-fully investigated ones. Specifically, how to build up flexible pricing model for both operators and end users, how to design efficient strategies to promote spectrum trading markets in new types of wireless architecture, how to develop technologies to enhance the network performance, etc. These are the areas that still need more efforts and still have quite some open questions to be investigated.

7. The Layman's Summary

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

With the rapid growth of mobile data and the poor indoor coverage, wireless operators are urgently seeking cost-effective solutions to achieve good indoor coverage with high capacity. Femtocell, which is a low-power small access point designed for indoor usage, is recognized as a promising approach to address these issues. Investing in the small-scale femto access points reduces the capital and operating expenditures of the wireless operators and creates opportunities to offer better service to end-users. In this project, we discussed various types of architectures for Self-Organizing Femtocell Networks, which can reduce the management and maintenance cost for dense femtocell networks. As an essential functionality in SON, cell outage detection is developed to autonomously detect macrocells or femtocells that are inoperative and unable to provide service. Based on the observation that spatial correlations among users can be extracted to cope with these challenges, in this work we proposed a Cooperative femtocell Outage Detection (COD) architecture, which outperforms the existing scheme in both communication overhead and detection accuracy. To control cross-tier interference, we proposed several core technologies, including fine-grained coordination, frame-level wideband spectrum adaptation, as well as efficient rate adaption that can achieve better spectrum efficiency for future wireless networks.

Part C: Research Output

8. Peer-reviewed journal publication(s) arising directly from this research project

(Please attach a copy of each 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	Acknowledged the support of this Joint Research Scheme	Accessible from the institutional repository
Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*	***(bold** the authors belonging to the project teams and denote the corresponding author with an asterisk*)*	*(with the volume, pages and other necessary publishing details specified)*	*(indicate the year ending of the relevant progress report)*	*(Yes or No)*	*(Yes or No)*	*(Yes or No)*
2014				W. Wang and Q. Zhang(*)	Local Cooperation Architecture for Self-Healing Femtocell Networks, IEEE Wireless Communications Magazine, Vol. 21, Issue 2, pp. 42-49, April 2014.	2015	No	Yes	Yes

2015				Y. Chen, P. Lin, and Q. Zhang (*)	LOTUS: Location-Aware Online Truthful Double Auction for Dynamic Spectrum Access, in IEEE on Wireless Communications (TWC), Vol. 14, No. 2, pp.1092-1099, Feb. 2015.	2015	No	Yes	Yes
2015				Y. Chen, L. Duan, J. Huang, and Q. Zhang (*)	Balancing Income and User Utility in Spectrum Allocation, in IEEE Trans. on Mobile Computing (TMC), Vol. 14, No. 12, pp. 2460-2473, Dec. 2015.	2015	Yes	Yes	Yes
2016				Q. Huang, Y. Gui, F. Wu(*), G. Chen, and Q. Zhang	A General Privacy Preserving Auction Mechanism for Secondary Spectrum Markets, in IEEE/ACM Transactions on Networking (ToN), Vol. 24, No. 3, pp.1881-1893, June 2016.	2015	Yes	Yes	Yes
2016				L. Wang, X. Qi, J. Xiao, K. Wu, M. Hamdi, and Q. Zhang (*)	Exploring Smart Pilot for Wireless Rate Adaptation, in IEEE on Wireless Communications (TWC), Vol. 15, Issue 7, pp. 4571-4582, July 2016.	2017	Yes	Yes	Yes
2016				W. Wang, Y. Chen, Q. Zhang (*), K. Wu, and J. Zhang	Less Transmissions, More Throughput: Bringing Carpool to Public WLANs, IEEE Trans. on Mobile Computing (TMC), Vol. 15, No. 5, pp. 1168-1181, May 2016.	2017	Yes	Yes	Yes
2016				W. Wang, Y. Chen, Q. Zhang (*), and T. Jiang	A Software-Defined Wireless Network Enabled Spectrum Management Architecture, in IEEE Communications Magazine, Vol. 54, Issue 1, Jan. 2016, pp.33-39.	2017	Yes	Yes	Yes

2017				W. Wang, Y. Chen, Z. Wang, J. Zhang, K. Wu, and Q. Zhang (*)	Wideband Spectrum Adaptation Without Coordination, in IEEE Trans. on Mobile Computing (TMC), Vol. 16, Issue 1, pp.243-256, Jan. 2017.	2017	Yes	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 delivered paper. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)

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 this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
April/ 2014/USA	HEAD: A Hybrid Spectrum Trading Framework for QoS-aware Secondary Users	IEEE Dyspan 2014	2015	No	Yes	Yes
April/ 2014/USA	LOTUS: Location-Aware Online Truthful Double Auction for Dynamic Spectrum Access	IEEE Dyspan 2014	2015	No	Yes	Yes
April/2015/ Hong Kong	Financial Analysis of 4G Network Deployment	IEEE Infocom 2015	2015	No	Yes	Yes
April/2015/ Hong Kong	Changing Channel without Strings: Coordination-Free Wideband Spectrum Adaptation	IEEE Infocom 2015	2015	No	Yes	Yes
April/2015/ Hong Kong	Enabling Ideal Time-Domain Arrangement for Today's Wireless LANs	IEEE Infocom 2015	2015	No	Yes	Yes
April/2016/ San Francisco	Battery-free Sensing Platform for Wearable Devices: The Synergy Between Two Feet	IEEE Infocom 2016	2017	Yes	Yes	Yes
April/2016/ San Francisco	From Rateless to Sampleless: Wi-Fi Connectivity Made Energy Efficient	IEEE Infocom 2016	2017	Yes	Yes	Yes
May/2016/ Kuala Lumpur	Managing Channel Bonding with Clear Channel Assessment in 802.11 Networks	IEEE ICC 2016	2017	Yes	Yes	Yes

10. 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
Yanjiao Chen	Ph.D.	Sept. 2010	Jan. 2015
Wei Wang	Ph.D.	Sept. 2010	Jan. 2015
Zhice Yang	Ph.D.	Sept. 2011	Aug. 2016
Lin Yang	Ph.D.	Sept. 2013	Aug. 2017
Qianyi Huang	Ph.D.	Sept. 2013	Aug. 2018

11. Other impact *(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, etc.)*

Nil