Report Year 1

Major Research and Education Activities

“**Collaborative Research: CCSS: D2D Wireless Networks: An Interference Nightmare or Resource Allocation Auspice”**

University of Houston (UH), grant ECCS-1405121;

**What are the major goals of the project?**

Mobile data traffic has dramatically increased in recent years with the emergence of smart devices. Device-to-Device (D2D) communications are expected to become a key feature supported by next generation cellular networks with advantages of: 1) extended coverage; 2) o²oading in cellular networks; 3) improved energy efficiency; 4) enhanced throughput and spectrum efficiency; and 5) creation of new services. Although D2D communications bring improvement in spectral efficiency and system capacity, it also causes *interference* to the cellular network as a result of spectrum sharing. Thus, efficient resource allocation and interference coordination must be addressed to guarantee a target performance level of the cellular communications. Moreover, due to the nature of the D2D networks, distributed algorithms are preferred. Game theory offers a set of mathematical tools to study the complex interactions among interdependent rational players and to predict their choices of strategies. In addition, some new types of access points such as femtocell/small cell can be jointly considered. Finally, the context aware and mobile social network aspects can be integrated into the proposed framework.

**What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities:

Apart from the standard base station relaying communications, user terminals in close proximity can also communicate directly through D2D communications. Due to the physical proximity and the potential reuse gain and hop gain, D2D communications can significantly increase network spectral-efficiency (SE) and energy-efficiency (EE). Similar to the existing short range wireless transmission techniques (e.g., Wi-Fi Direct, Bluetooth, and UWB), D2D communications can also bring low transmission delay. Furthermore, D2D communications utilize the licensed spectrum bands and thus can guarantee uniform service provision and quality-of-service (QoS). Moreover, D2D communications can offload traffic and avoid congestion in the cellular core network. In addition, D2D communications have also been considered as cost effective solution for public safety service in case of lack of network coverage in 3GPP LTE-Advanced.

Specific Objectives:

1. *Resource Allocation for Spectral Efficiency Maximization:* The resource allocation, such as admission control and power management to D2D communications, requires elaborate coordination so as to improve the overall performance of D2D networks. The PIs propose a resource allocation framework to improve performance of mobile D2D communications as an underlay in cellular networks, using techniques such as graph theory and matching theory to coordinate D2D pairs and reuse candidates, so that system performance and individual QoS can be optimized.
2. *Game Theoretical Distributive Scheme:* To optimize the system performance over the resource sharing of both D2D and cellular modes, the PIs first plan to introduce a reverse iterative combinatorial auction as the allocation mechanism. In the auction, all the spectrum resources are considered as a set of resource units, which as bidders compete to obtain business while the packages of the D2D pairs are auctioned off as goods in each auction round. In addition, the PIs propose a Stackelberg game framework in which cellular UTs and D2D UTs are grouped as leaders and followers, respectively. The follower D2D UTs are the followers who buy channel resources from the leader cellular users. The PIs analyze the equilibrium of the game, and propose an algorithm for joint scheduling and resource allocation in a distributed fashion. Other approaches, such as coalition game, contract theory, and stochastic game, will also be investigated.
3. *Joint Consideration with Femtocell/Small Cell:* By operating in the licensed spectrum, femtocells/small cells provide users with higher capacity and coverage, and will be offered by the cellular operator to enable high data rate local services in future LTE-Advanced networks. However, the tight integration of femtocell/small cell and D2D communications creates a challenge for existing network design, and is seldom studied in the literature. The PIs plan to devise open access for femtocell together with D2D LTE-Advanced networks in order to optimize network connectivity, coverage, system performance, and balance.
4. *Context Aware and Social Aware D2D Network:* The PIs plan to design, study, and optimize a context aware framework for resource management in D2D networks. Moreover, the PIs will develop social-aware D2D protocols, which offer insights into how to utilize the social relationship to design efficient and practical algorithms. This cross-layer approach will boost the network performance in terms of data rates, latency, and overall quality. The developed framework will provide significant direct performance gains to interactive service classes, such as multimedia communications and mobile network gaming, which in turn will improve the overall performance of the wireless network.

Significant results:

The research has resulted in 1 book publication, 9 journal papers, and 2 conference papers:

1. Lingyang Song, Dusit Niyato, Zhu Han, and Ekram Hossain, Wireless Deviceto-Device Communications and Networks, Cambridge University Press, UK, 2015 (Chinese version by China Machine Press 2016).
2. Bentao Zhang, Yong Li, Depeng Jin, and Zhu Han, “Network Science Approach for Device Discovery in Mobile Device-to-Device Communications,” to appear, IEEE Transactions on Vehicular Technology.
3. Yong Li, Depeng Jin, Pan Hui, and Zhu Han, “Optimal Base Station Scheduling for Device-to-Device Communication Underlaying Cellular Networks,” to appear IEEE Journal on Selected Areas on Communications, Special Issue on Device-to Device Communications in Cellular Networks.
4. Yong Xiao, Zhu Han, Kwang-Cheng Chen, Chau Yuen, Luiz A. DaSilva, “A Bayesian Overlapping Coalition Formation Game for Device-to-Device Spectrum Sharing in Cellular Networks,” to appear, IEEE Transactions on Wireless Communications.
5. Yanru Zhang, Lingyang Song, Walid Saad, Zaher Dawy, and Zhu Han, “Contract Theory for Socially-Aware Device-to-Device Communications,” invited Journal of Signal Processing Systems, special issue on Ultra High Performance and High Efficiency in 5G Mobile Networks.
6. Yunan Gu, Yanru Zhang, Miao Pan, and Zhu Han, “Matching and Cheating in Device to Device Communications Underlaying Cellular Networks,” to appear, IEEE Journal on Selected Areas on Communications, Special Issue on Recent Advances in Heterogeneous Cellular Networks.
7. Yanru Zhang, Lingyang Song, Walid Saad, Zaher Dawy, and Zhu Han, “Contract Theory for Optimized Device-to-Device Communication in Cellular Networks,” to appear, IEEE Journal on Selected Areas on Communications, Special Issue on Recent Advances in Heterogeneous Cellular Networks.
8. Kae Won Choi and Zhu Han, “Device-to-Device Discovery for Proximity-Based Service in LTE-Advanced System,” accepted, IEEE Journal on Selected Areas on Communications, Special Issue on Device-to-Device Communications in Cellular Networks.
9. Yanru Zhang, Erte Pan, Lingyang Song, Walid Saad, Zaher Dawy, and Zhu Han, “Social Network Aware Device-to-Device Communication in Wireless Networks,” IEEE Transactions on Wireless Communications, vol. 14, no. 1, p.p. 177–190, January 2015.
10. Yong Li, Depeng Jin, Jian Yuan, and Zhu Han, “Coalitional Games for Resource Allocation in the Device-to-Device Uplink Underlaying Cellular Networks,” IEEE Transactions on Wireless Communications, vol. 13, no. 7, p.p. 3965–3977, July 2014.
11. Yunan Gu, Yanru Zhang, Miao Pan, and Zhu Han, “Cheating in Matching of Device to Device Pairs in Cellular Networks,” IEEE Global Communications Conference, December, Austin, TX, 2014.
12. Jia Hao, Hongliang Zhang, Lingyang Song, and Zhu Han, “Graph-based Resource Allocation for Device-to-Device Communications Aided Cellular Network,” IEEE International Conference on Communications in China (ICCC), Shanghai, China, October 2014.

Key outcomes or Other achievements:

The key outcomes are the game theoretically approaches for D2D resource allocation. Specifically, we employ the matching theory and contract theory, respectively by two female Ph.D. candidates, Ms. Yanru Zhang and Ms. Yunan Gu.

**What opportunities for training and professional development has the project provided?**

The proposed research activities support the training of both graduate and undergraduate students. The PIs have a successful track record in supervising undergraduate and graduate research. Graduate students from both institutions will work as a driving force. These students can gain valuable experience to carry out their future independent research projects by conducting research activities and building the testbed. Moreover, upon funding of this project, the PIs request Research Experience for Undergraduate (REU) supplementary funding from NSF to support several undergraduates to assist proposed research and motivate them to continue their research in graduate school. These undergraduate students can work closely with graduate students on various projects, providing them with a forum and a unique opportunity to interact and exchange ideas with graduate students and learn the basics about conducting research. Last, the proposed testbed infrastructure has been made available to all the students who are interested in experimenting with and learning about wireless networks, in general, and D2D wireless networks, in particular.

The PIs are highly committed to teaching. The PIs have derived course projects to motivate the students in their wireless networking courses, with an objective of motivating and educating our innovative students in science and engineering. Research intensive practice-oriented education has been integrated into the classroom by introducing hands-on projects involving both programming and experiment. The PIs instruct the students on the design principles and applications of wireless networks. Lectures from the wireless practitioners and system administrators provide useful information to stimulate students' interest and train their problem solving skills. We have continuously improved these courses and gather hands-on teaching materials. Problems and course structure and evaluation information have been compiled and made available on our web page. Moreover, the PIs continue to integrate the research results into programs, such as IEEE tutorials and IEEE distinguished lectures that the PIs actively participate in. Additionally, the PIs plans to incorporate research activities into undergraduate senior design capstone projects. Through the project, the PIs also explore efficient pedagogical approaches and promote the integration of research and education.

**How have the results been disseminated to communities of interest?**

We have done the following three conference tutorials for D2D communication and one keynote speak.

1. “Game-theoretic Methods for Device-to-Device Communications”, IEEE International Conference on Communication (ICC).
2. “Wireless Device-to-Device Communications and Networks”, IEEE Global Communications Conference (Globecom).
3. “Device to Device Communication for Next Generation Wireless Networks”, IEEE International Conference on Communication in China (ICCC).
4. Keynote Speak, “Wireless Device-to-Device Communications and Game Theoretical Resource Allocation,” International Workshop on Wireless Networks: Communication, Cooperation and Competition, Hammamet, Tunisia, May 2014.

**What do you plan to do during the next reporting period to accomplish the goals?**

**Beyond continuing the research by two female Ph.D. students, we plan to explore the REU and undergraduate students for test best and Prototype. We plan to build a testbed with USRP2 and smart phones in both institutes. The PIs plan to accomplish a number of experimental tasks to validate the effectiveness of our approaches and methodologies. The codes and tools will be available through the Lab websites for better dissemination.**

**What is the impact on the development of the principal discipline(s) of the project?**

The proposed activities have been conducted by an interdisciplinary team who conducts researches in several critical research areas including resource allocation over D2D networks, especially for distributed cross-layer optimization. The fundamental results to be obtained from this project enable transformative techniques that can lead to improved performance of the next generation wireless networks. The results will be publicly available through publications and open source software release. Ultimately, the proposed interdisciplinary framework provides a blueprint towards building new perspectives on future wireless network design.

**What is the impact on other disciplines?**

The technical merit and impacts of this project are both fundamental and applied, including new algorithms, methodologies, technologies, and tools. The problems to be studied are pragmatically and their solutions are transformative, and thus, can broaden the scope of applications in D2D networks and lead to promising economic impact. On mathematics, this project acts as an important source for practical problems that will lead to the further development of game theory. This project can also provide a blueprint and platform for deployment and experiment of industrial D2D networking systems. Our research results will be disseminated broadly through a number of channels including high-quality international conferences, academic journals, seminars, and workshops. The PIs are committed to make the hardware and software available to the research community at large. All software tools are open-source, and hence are available to other researchers in the field.

**What is the impact on the development of human resources?**

Our team is strongly committed to provide early intervention, experiential learning, and one-on-one cross-age contact as tools to strengthen the student pipeline in the science, technology, engineering, and mathematics (STEM) fields. PI Han has participated for several years in summer outreach activities for high school students. This project will help PIs to arrange such outreach activities for high school students. These efforts will be expanded to include summer programs leading to opportunities for high school teachers in both regions to learn and participate in innovative research in cross-disciplinary fields of computer science and engineering.

**What is the impact on physical resources that form infrastructure?**

**N/A**

**What is the impact on institutional resources that form infrastructure?**

**N/A**

**What is the impact on information resources that form infrastructure?**

**N/A**

**What is the impact on technology transfer?**

Dr. Han is planning some short courses for Qualcomm to disseminate this D2D research to industry.

**What is the impact on society beyond science and technology?**

**We are planning to have some social network research based on the D2D research, since D2D can have the location information.**