

[My Desktop](#)
[Prepare & Submit Proposals](#)
[Proposal Status](#)
[Proposal Functions](#)
[Awards & Reporting](#)
[Notifications & Requests](#)
[Project Reports](#)
[Submit Images/Videos](#)
[Award Functions](#)
[Manage Financials](#)
[Program Income Reporting](#)
[Grantee Cash Management Section Contacts](#)
[Administration](#)
[Lookup NSF ID](#)

Preview of Award 1526769 - Annual Project Report

[Cover](#) |
[Accomplishments](#) |
[Products](#) |
[Participants/Organizations](#) |
[Impacts](#) |
[Changes/Problems](#)

Cover

Federal Agency and Organization Element to Which Report is Submitted:	4900
Federal Grant or Other Identifying Number Assigned by Agency:	1526769
Project Title:	NeTS: Small: Collaborative Research: Network-Centric Mobile Cloud Computing
PD/PI Name:	Wei Gao, Principal Investigator
Recipient Organization:	University of Tennessee Knoxville
Project/Grant Period:	10/01/2015 - 09/30/2018
Reporting Period:	10/01/2016 - 09/30/2017
Submitting Official (if other than PD\PI):	Wei Gao Principal Investigator
Submission Date:	10/02/2017
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	Wei Gao

Accomplishments

* What are the major goals of the project?

Mobile cloud computing (MCC) has been used to address the resource limitation of mobile devices by migrating expensive local computations to the cloud. However, transmitting data wirelessly from mobile devices to the cloud also consumes energy. Hence, the key problem of MCC is how to minimize the energy consumption while preserving the mobile application performance. Different from traditional solutions which focus on reducing the cost of wireless transmission solely from the application perspective, this project focuses on designing MCC schemes from a network-centric perspective, by investigating, formulating, and mitigating the impact of special characteristics of wireless networks on the energy efficiency of MCC. The proposed research could benefit end users with various mobile devices by extending their battery lifetime and improving their performance.

This project aims to improve the performance of MCC by mitigating the impacts of two special characteristics of wireless

networks: the long-tail problem at the wireless interface and the quality variations of the wireless link. More specifically, this project consists of three closely intertwined research thrusts: (i) reducing the amount of tail energy when transmitting the program states to the remote cloud, while ensuring that the performance requirements of mobile applications can be met; (ii) mitigating the impact of wireless link quality on both energy and performance, and minimizing the degradation of application performance when the wireless link quality is low; and (iii) exploiting the difference of wireless link quality among mobile users to further improve the energy efficiency of MCC via user cooperation. An experimental testbed will be developed to investigate the practical impact of wireless network characteristics on MCC and evaluate the proposed MCC schemes.

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

Major Activities:

Current MCC solutions have limitations in that they reduce the cost of wireless transmission solely from the application perspective, by reducing the size of program states being transmitted according to the network bandwidth and programs' computational complexity. They have minimal explorations into the special characteristics of wireless networks, which affect the energy consumption of wireless transmission and have a pivotal role in energy-efficient MCC. Ignorance of these wireless network characteristics is also the major factor hindering practical integration of mobile devices into the cloud. To efficiently investigate, formulate and mitigate the impact of special characteristics of wireless networks on the energy efficiency of remote program execution in MCC, we had the following major activities in the past year.

First, appropriate scheduling over multiple concurrent communication links is crucial to the efficiency of MCC operations in wireless networks. Existing wireless network scheduling algorithms usually formulate the scheduling problem as solving the NP-hard Maximum Weighted Independent Set (MWIS) problem over a network conflict graph, but are designed to provide approximations to global optimality via distributed operations in wireless networks. Therefore, these algorithms will need to be frequently operated over the entire network in cases of network dynamics, regardless of the actual network area being affected by these dynamics. Instead, in order to reduce the computation and communication overhead when scheduling wireless networks in such dynamic environmental settings, we developed distributed algorithms that adaptively constrain network scheduling within the limited scope where network dynamics occur. The scheduling results from such limited operations are then combined with the previous scheduling results over the remaining portions of the network, hence still providing guaranteed network throughput. The performance of our proposed algorithms has been validated by formal analysis, and been verified by both numerical studies and real-world experiments.

Second, we have been focusing on constructing a personal mobile cloud, which is able to efficiently execute mobile programs at remote cloud locations and eliminate the restriction of individual mobile devices' capability in computation and communication. Our basic idea of designing such a personal mobile cloud is to incorporate and interconnect all the mobile devices owned by a user via wireless links in a generic manner, so that these devices can flexibly share system resources with each other, augmenting the mobile computing capability provided to the user. For example, wearables can save their local battery by exploiting the computational power of nearby stronger devices, while providing their sensory data to these devices and facilitate their context-aware applications. We have developed a generic resource sharing framework across heterogeneous types of mobile hardware and software, while hiding all the low-layer details of device driver operations from user applications. Interconnection between mobile devices, then, is realized via remote access and invocation of these OS services.

Education Activities:

Two PhD students have worked on the project. Some of the research results have been integrated with the education curricula at University of Tennessee, Knoxville. For example, we have added smartphone techniques to the contents of our undergraduate

course “ECE455: Embedded System Design” and provided the students with the opportunity of working with the Android OS and off-the-shelf mobile devices.

Specific Objectives: The goal of this research is to design MCC schemes from a *network-centric* perspective, by investigating, formulating, and mitigating the impact of special characteristics of wireless networks on the energy efficiency of remote program execution in MCC. We consider these characteristics in two aspects: i) *long-tail problem at the wireless interface*, i.e., the cellular radio interface stays in the high-power state for some time after each data transmission, and ii) *quality of the wireless link*, which may be highly dynamic due to various environmental factors. We will incorporate both aspects to ensure that each program state is transmitted to the cloud in the most energy-efficient manner. However, such network-centric design is challenging due to the following reasons. First, due to the low bandwidth and long delay of cellular network links, most existing works focus on transmitting program states via WiFi instead of cellular networks, and remote execution of mobile programs would be impossible when WiFi is unavailable. Recent deployment of 4G networks such as LTE eliminates the bandwidth and delay barrier of exploiting cellular networks in MCC and hence enables uninterrupted access to the remote cloud, but incurs a large amount of additional energy cost due to the long-tail problem. Second, the condition of wireless link quality could be highly dynamic in practice, and should also be considered to ensure energy-efficient MCC. Most existing MCC techniques, however, inappropriately assume that the wireless link quality is stable over time. To address the above challenges, our work incorporates the following two objectives.

Our first objective is to reduce the amount of energy being consumed during the tail times of wireless data transmissions for MCC operations. In MCC, the tail energy should be reduced with respect to the performance requirements of mobile applications. Existing work reduces the tail energy by deferring transmissions of program states and sending them as bundles, but greatly increases the response time of mobile applications. To address this problem, we need to decide whether a mobile program should be executed locally or remotely, to minimize the energy consumption without deferring the program execution. Such decision will be made according to the amount of tail energy incurred by the transmission of program states. Afterwards, based on these decisions of remote program execution, we further reduce the tail energy by deferring the execution of a mobile application within its delay constraint and scheduling the transmissions of program states accordingly.

Our second objective is to mitigate the impact of wireless network dynamics, which affect the quality of wireless links, on both the energy efficiency and performance of MCC. When the wireless link quality degrades, the amount of data being transmitted via wireless links will be limited to save energy. In this case, we shall preserve the mobile application performance by only transmitting the most important program states and maximizing the amount of mobile programs being executed at the remote cloud. Being different from existing work which determines the importance of a program state solely from the program’s computational complexity, we need to develop fine-grained program parsing techniques to evaluate the importance of each memory field in a program state to executing other programs. Application partitioning strategy will then be developed based on the importance of program states.

Significant Results: First, we have made theoretical efforts to reduce the computation and communication overhead of wireless network scheduling, without degrading the wireless communication performance over multiple concurrent wireless links. By experimentally investigating wireless network dynamics in different types of practical application scenarios, we observe that these dynamics in wireless networks usually affect only a small portion of the network at any specific moment, when the rest major portion of the network remains stable and unaffected. Based on this observation, we developed distributed algorithms that schedule wireless networks only within the limited scope where network dynamics occur. Our proposed algorithms combine the scheduling

results from such limited operations with the previous scheduling results over the remaining portions of the network, hence still providing guaranteed network throughput with much lower overhead. We conducted formal analysis that demonstrates the correctness of our scheduling algorithms on avoiding network interference, and also shows that our algorithms provide a fixed approximation ratio to optimality. We evaluated the performance and overhead of our scheduling algorithms using both numerical studies with large-scale conflict graphs and real-world experiments over software-defined radio platforms that take practical wireless channel conditions into account.

Second, we envision that the key to building the personal mobile cloud and realizing generic interconnection across heterogeneous mobile devices is to develop an efficient framework for resource sharing between these devices, which appropriately masks the hardware and software heterogeneity in mobile systems from each other. Development of such a resource sharing framework, however, is challenging due to the close interaction between mobile hardware and software. A framework at the lower layer of mobile OS hierarchy unifies the heterogeneous resource requests of mobile applications, but has to tackle with individual hardware drivers which are operated in intrinsically different ways and hence incurs a tremendous amount of re-engineering efforts. Sharing system resources at the application layer, on the other hand, is able to access mobile hardware through a generic OS interface, but has to be associated with specific data transfer protocols and hence has limited generality. Instead, our work develops such a generic resource sharing framework towards a practical personal mobile cloud as a middleware in the mobile OS, which exploits the existing mobile OS services to share resources between mobile devices. These services hide the low-layer details of device driver operations while providing unified data access APIs to user applications. Interconnection between mobile devices, then, could be realized via remote access and invocation of these OS services. Since these services are executed as a standalone system process by the OS kernel and are separated from application processes, remote service invocation can be done via inter-process communication (IPC) between mobile systems without involving complicated issues such as memory referencing and synchronization. As a result, any new device can be incorporated into the mobile cloud by inserting our framework into its OS, without modifying the OS kernel, our framework itself, or the source code of any mobile application.

Key outcomes or Other achievements:

The results of our work “Scheduling Dynamic Wireless Networks with Limited Operations,” has been accepted by the highly competitive *IEEE International Conference on Network Protocols (ICNP 2016)*, which has an acceptance ratio of 20%.

The results of our work “Interconnecting Heterogeneous Devices in the Personal Mobile Cloud,” has been accepted by the highly competitive *IEEE Conference on Computer Communications (INFOCOM 2017)*, which has an acceptance ratio of 20%.

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

Two PhD students have worked on the project, and the research results have been published at various academic conferences.

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

Our research work in this project has resulted in two conference papers. These publications will help people better understand our novel techniques on exploiting system and network dynamics in mobile clouds, and further apply these techniques to improve the performance and energy efficiency of MCC applications in practice. We have also given seminar and summer camp talks to high school students to stimulate their interest in engineering majors.

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

We will further investigate and develop techniques to ensure the efficiency of MCC operations under highly dynamic conditions of the wireless network channel. In particular, when the wireless link quality degrades or the wireless channel is

congested, we will further develop efficient wireless transmission strategies to ensure that the MCC traffic could be timely delivered between mobile devices and the remote cloud without being delayed and interfered. In this case, we will adaptively preserve the mobile application performance by utilizing the wireless spectrum in the most efficient manner. Furthermore, the energy efficiency of MCC could be further improved by cooperation among mobile users. Existing schemes focus on cooperative workload balancing among collocated mobile devices, but cannot reduce the total energy cost over all mobile devices. To address this problem, we will reduce the tail energy by aggregating the transmissions of program states from multiple co-located mobile devices to one device, called the proxy. Such a proxy will be selected based on the quality of wireless links at different mobile devices, to ensure that the program states are only transmitted via wireless links with good quality.

Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers

Haoyang Lu and Wei Gao (2016). Scheduling Dynamic Wireless Networks with Limited Operations. *Proceedings of the 24th IEEE International Conference on Network Protocols (ICNP)*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Yong Li and Wei Gao (2017). Interconnecting Heterogeneous Devices in the Personal Mobile Cloud. *Proceedings of the 36th IEEE Conference on Computer Communications (INFOCOM)*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Licenses

Other Conference Presentations / Papers

Other Products

Other Publications

Patents

Technologies or Techniques

Thesis/Dissertations

Websites

Project website

http://www.pitt.edu/~weigao/reporting/mcc_network_centric.html

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Gao, Wei	PD/PI	2
Li, Yong	Graduate Student (research assistant)	1
Lu, Haoyang	Graduate Student (research assistant)	4

Full details of individuals who have worked on the project:

Wei Gao**Email:** weigao@utk.edu**Most Senior Project Role:** PD/PI**Nearest Person Month Worked:** 2**Contribution to the Project:** Manage the project team. Designed and implemented the wireless network scheduling protocols with limited operations. Designed the generic resource sharing framework towards a personal mobile cloud.**Funding Support:** This grant.**International Collaboration:** No**International Travel:** No

Yong Li**Email:** yli118@vols.utk.edu**Most Senior Project Role:** Graduate Student (research assistant)**Nearest Person Month Worked:** 1**Contribution to the Project:** Contribute to the design and implementation of various MCC schemes and protocols, especially the generic resource sharing framework for personal mobile cloud.**Funding Support:** this grant.**International Collaboration:** No**International Travel:** No

Haoyang Lu**Email:** hlu9@vols.utk.edu**Most Senior Project Role:** Graduate Student (research assistant)**Nearest Person Month Worked:** 4**Contribution to the Project:** Design and implementation of the wireless network scheduling protocols with limited operations.**Funding Support:** this grant.**International Collaboration:** No**International Travel:** Yes, Singapore - 0 years, 0 months, 7 days

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
Guohong Cao	Academic Institution	University Park, PA

Full details of organizations that have been involved as partners:**Guohong Cao****Organization Type:** Academic Institution**Organization Location:** University Park, PA**Partner's Contribution to the Project:**

Collaborative Research

More Detail on Partner and Contribution: Dr. Guohong Cao from Pennsylvania State University has been actively involved in discussing the design and implementation of our application-aware traffic scheduling work.

What other collaborators or contacts have been involved?

Nothing to report

Impacts

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

MCC can greatly benefit a large variety of mobile devices ranging from smartphones to embedded sensor devices, and from smart watches to wearable medical devices. The transformative nature of the proposed research is to completely redesign MCC from a network-centric perspective, and to turn various system modeling and formal analysis techniques into actionable distributed algorithms and design strategies that apply to practical mobile cloud systems. It will investigate the essential factors determining the energy efficiency of MCC that are tightly coupled with the special characteristics of wireless networks, and will inspire further theoretical and systematic studies that can open up new areas of research. To summarize, the research output will have the following impacts. First, it leads to a new design philosophy for MCC that is pivotal to practical integration of mobile devices into the cloud. Second, it introduces novel solutions to deal with the long-tail problem related to the wireless radio interface that is vital to energy-efficient MCC. Third, this work can spawn a new area of research on mitigating the impact of wireless link quality on MCC. Fourth, the techniques of cooperative wireless link selection in MCC are likely to foster further research along this direction. Finally, the developed testbed as a unique research facility will benefit the whole research community.

What is the impact on other disciplines?

The mobile cloud is a typical example of mobile computing systems with complex dynamics rooted in the system's execution. Being able to precisely characterize and appropriately exploit these dynamics to improve the system efficiency and adaptability has a direct and immediate impact on a large variety of ubiquitous computing and cyber-physical systems.

What is the impact on the development of human resources?

Many of the research results have been integrated into the undergraduate curricula at the University of Tennessee, by adopting many perspectives of the research results for undergraduate students' course projects and senior design topics. The project has supported two PhD students working on their dissertations. The involvement of the graduate and undergraduate students into this research will prepare them for leadership roles in computer science research, academia, and industry.

What is the impact on physical resources that form infrastructure?

Nothing to report.

What is the impact on institutional resources that form infrastructure?

Nothing to report.

What is the impact on information resources that form infrastructure?

Nothing to report.

What is the impact on technology transfer?

Nothing to report.

What is the impact on society beyond science and technology?

Nothing to report.

Changes/Problems

Changes in approach and reason for change

Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

Nothing to report.

Changes that have a significant impact on expenditures

Nothing to report.

Significant changes in use or care of human subjects

Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.