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Federal Agency and Organization Element to Which Report is Submitted:	4900
Federal Grant or Other Identifying Number Assigned by Agency:	1821874
Project Title:	CRII: NeTS: Exploiting System and Network Dynamics in Mobile Clouds
PD/PI Name:	Wei Gao, Principal Investigator
Recipient Organization:	University of Pittsburgh
Project/Grant Period:	09/01/2017 - 05/31/2018
Reporting Period:	06/01/2017 - 05/31/2018
Submitting Official (if other than PD\PI):	Wei Gao Principal Investigator
Submission Date:	10/13/2018
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) bridges the gap between the limited capabilities of mobile devices and the increasing complexity of mobile applications, by offloading the computational workloads from local devices to the remote cloud. However, the effectiveness of mobile cloud computing could be impaired by the dynamic nature of system and network contexts, which lead to heterogeneous mobile application

behaviors and seriously reduce the appropriateness of workload offloading decisions. This project exploits these critical dynamics in mobile clouds that are indispensable to efficient, prompt, and reliable workload offloading. More specifically, it addresses three closely intertwined research issues in mobile cloud computing. The first part investigates how to analytically formulate the stochastic characteristics of run-time application executions, based on which the workload offloading decisions are probabilistically made and systematic techniques are developed to practically enforce such decisions. The second part incorporates the contexts and performance requirements of mobile cloud applications into the design of wireless networks, so as to adaptively balance between the wireless energy cost and application performance in mobile clouds through fundamental redesign of wireless transmission scheduling algorithms. The third part focuses on testbed development to automatically investigate the run-time system and network dynamics of mobile cloud applications in practice. This testbed consists of off-the-shelf smartphones and wearable devices, and enables in-field experiments for evaluating the performance of the proposed techniques and system designs.

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

Major Activities:

Built on the accomplishments in the past years, we have further designed and implemented wireless network protocols and systems to improve the data throughput, reliability and versatility of wireless links connecting mobile devices and the remote cloud, so as to ensure that network dynamics have minimum impact on the mobile cloud operations. Since the PI has moved from University of Tennessee Knoxville to University of Pittsburgh and this move requires recruiting new graduate students working on this project, we asked for a nine-month no-cost extension (9/1/2017 – 5/31/2018). During this reporting period, we have focused on improving the throughput and minimizing the latency of wireless data transmission over a high dynamic wireless link, and also explored the possibility of retaining the wireless network performance among heterogeneous types of wireless devices that interfere with each other. The major activities include:

First, we have designed and evaluated a new PHY wireless modulation technique, which transforms the available choices for wireless link rate adaptation from discrete to continuous, so that the link rate being chosen is always optimal for any channel condition and the wireless channel throughput is hence optimized under highly severe or dynamic channel conditions. This technique aims to address the current under-utilization of wireless spectrum in various mobile cloud scenarios, especially those at large public facilities such as massive transportation systems, shopping malls and museums, where the wireless network performance may experience serious degradation due to the long communication distance or complicated indoor layout. In these cases, our technique will be critical to ensure sufficient wireless network throughput for transmitting the mobile program data for mobile cloud computing.

Second, we aim to retain the wireless network performance when heterogeneous types of mobile devices are connected to the remote cloud via different wireless technologies, by enabling cross-technology coexistence without incurring any additional transmission delay or

signal processing overhead on these weak devices. To do this, our key insight is the different wireless technologies' diversity in spectrum utilization, which balance between the channel bandwidth, transmission range and power consumption in different ways. Based on this insight, we adaptively adjust the wireless technology operated by strong wireless devices to reserve a minor portion of its occupied spectrum, to which the wireless channel operated by weak devices is being embedded. In this way, the mobile cloud performance being provided to these devices can be retained with zero extra overhead.

Third, we have also extended our previous work on minimizing the wireless transmission delay over a congested wireless channel, by implementing our design of a PHY-layer wireless side channel over custom wireless hardware. Such implementation allows real-time wireless networking over such a side channel, and retains full compatibility with commodity wireless devices. Based on this implementation, we are able to apply our PHY wireless design to a large collection of practical mobile computing platforms, so as to improve the mobile cloud computing performance in practice.

Education Activities:

Two PhD students have worked on this project. Some of the research results have been integrated with the education curriculum at University of Pittsburgh. For example, we have added mobile and wearable computing techniques to our undergraduate course “ECE 1160: Introduction to Embedded System Design”.

Specific Objectives:

The primary research objectives of this project in the past reporting period is to design new wireless technologies to ensure optimal and reliable performance of the wireless link connecting mobile devices to the remote cloud in diverse application scenarios. More specifically, we focus on the following detailed research objectives:

1. We aim to ensure that the wireless link connecting mobile devices to the remote cloud can always provide sufficient throughput for transmitting the mobile program data being remotely executed, even if the link condition is highly dynamic or severe due to link congestion or signal quality degradation.

2. We require the performance of such a wireless link to be resistant to any wireless interference from other wireless devices that are concurrently transmitting over the same frequency band.

3. We also require the data transmission latency between mobile devices and the remote cloud to be always minimized, even through a highly congested wireless link. Such requirement, however, cannot be satisfied by traditional networking techniques such as QoS or TCP flow control, which fail when the amount of network traffic increases.

Significant Results:

Based on the above research objectives, our research activities in the last reporting period have resulted in the following results:

First, we developed a new PHY-layer wireless modulation technique, named vMod (VLC-based modulation), which is a better solution towards rateless networking that always provides maximum wireless throughput over highly dynamic wireless links. Being different from existing rateless codes that regardlessly send and decode rateless data chunks with high communication and computation overhead, vMod transforms the available choices for link rate adaptation from discrete to continuous, so that the link rate being chosen is always optimal for any channel condition. The key technical contribution of vMod is that it can modulate an arbitrarily fractional number of data bits into a wireless data symbol, while preserving every individual symbol to be independent from others. In this way, it can provide any link rate that is supported by the channel condition. In order to encode a fractional number of data bits into a symbol that contains an integer number of constellation points, our key insight is to design a Variable-Length Code (VLC) and split the data bitstream into variable-length codewords, which are then mapped to constellation points in symbols. Hence, each symbol randomly carries a variable amount of data bits, and any link rate can be statistically achieved by adjusting the range and constitution of codeword lengths. We implemented vMod over USRP with GNURadio toolkit, based on a 5 GHz WiFi transceiver. Minimum modification is conducted over WiFi PHY and MAC. Based on this implementation, we evaluated vMod under dynamic channel conditions, and also compared vMod with existing rateless codes (Strider and Spinal codes). The experiment results show that vMod scales well with the dynamic channel conditions and improves the WiFi throughput by 30% over a single narrowband link, but consumes up to 95% less computation and communication overhead.

Second, we also made research efforts on preventing mobile devices operating different wireless technologies from interfering with each other, when they simultaneously transmit data over the same spectrum. Being different from existing work which usually address such interference at a cost of extra transmission delay and local signal processing overhead, our approach fundamentally avoids any extra overhead or performance degradation at resource-constrained mobile devices, by migrating any necessary wireless PHY operations to other strong wireless devices. For example, a strong wireless device selectively avoids transmitting WiFi data through some of the OFDM subcarriers, so that the spectrum occupied by these subcarriers becomes available for a concurrent ZigBee channel. Since only a small portion of subcarriers needs to be avoided, we are able to flexibly schedule such spectrum reservation over time, so as to utilize the ZigBee's built-in error correction capabilities for minimum packet reception errors. We have implemented our design over customizable wireless hardware, and evaluated its performance over commodity wireless transceivers. Our experiment results show that we can achieve 99% ZigBee packet reception rate over a fully occupied 20MHz WiFi channel, without incurring any extra delay to ZigBee traffic. At the same time, we effectively control the WiFi throughput loss due to spectrum reservation within 5%, and hence has only negligible impact to most wireless applications.

Third, we further expanded our previous design of a high-throughput wireless side channel (see our previous paper published at ACM MobiHoc 2016) and implemented this design over the WARP v3 SDR boards, which is a FPGA-based wireless hardware platform and allows hardware-based implementation of a fully functional wireless transceiver over its FPGA core. It hence allows real-time wireless networking and full compatibility with commodity wireless devices: since all the Tx and Rx operations are being conducted over the FPGA hardware instead of via GNU software emulation, it incurs near-zero computation delay to our proposed side channel operation for simulating the performance in commodity wireless devices. Our implementation requires minimal modification to the existing wireless system. We added a subsystem to commodity WiFi PHY. Such subsystem has minimal complexity, by applying a few multiplexers and three multipliers into our FPGA core. This implementation allows practical integration of our side channel design into commodity wireless devices.

Key outcomes or Other achievements: Our research activities have resulted in three journal or conference papers being published, accepted or under review.

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

Two PhD students have worked on this project towards their dissertations, and some results have been published.

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

Our publications will help people understand our novel techniques on supporting efficient and reliable mobile cloud operations. We have given several seminars to high school and undergraduate students at different US institutions (e.g., University of Pittsburgh, Carnegie Mellon University and Pennsylvania State University) to attract them to engineering majors.

Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers

Haoyang Lu and Wei Gao (2018). Continuous Wireless Link Rates for Internet of Things. *in Proceedings of the 17th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN)*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Ruirong Chen and Wei Gao (2019). Enabling Cross-Technology Coexistence for Extremely Weak Wireless Devices. *IEEE INFOCOM*. . Status = UNDER_REVIEW; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Ruirong Chen, Haoyang Lu and Wei Gao (2018). Minimizing Wireless Delay with a High-Throughput Side Channel. *IEEE Transactions on Mobile Computing*. . Status = ACCEPTED; 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_dynamics.html

Project website

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Gao, Wei	PD/PI	3
Chen, Ruirong	Graduate Student (research assistant)	3
Lu, Haoyang	Graduate Student (research assistant)	3

Full details of individuals who have worked on the project:

Wei Gao
Email: weigao@pitt.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 3

Contribution to the Project: Lead and manage the project.

Funding Support: This project.

International Collaboration: No
International Travel: No

Ruirong Chen
Email: RUC28@pitt.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Developed and implemented the wireless technique of cross-technology coexistence over extremely weak wireless devices.

Funding Support: This project

International Collaboration: No
International Travel: No

Haoyang Lu
Email: haoyanglu@pitt.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Develop and implement the wireless technologies of continuous link rates.

Funding Support: This project.

International Collaboration: No
International Travel: Yes, Portugal - 0 years, 0 months, 4 days

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What other organizations have been involved as partners?
Nothing to report.

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?

Contextual awareness enabled by recent emergence of cognitive mobile applications and wearable devices fundamentally transforms the way people behave and interact with the environment, but also imposes serious challenges on the capabilities and battery lifetime of mobile devices. This project aims to completely rethink how mobile cloud computing could be practically realized to alleviate the local computational burden and adaptively support contextual awareness over heterogeneous mobile scenarios, by turning analytical formulations of the various system and network dynamics into actionable system design strategies. The results from mobile computing system design and wireless network scheduling protocols are likely to foster further research along these directions. The research can also spawn a new area of research on efficiently interconnecting heterogeneous mobile devices towards a personal mobile cloud. Finally, the analysis techniques, the evaluation methodology and systems developed in this research will be valuable for future undertakings.

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 and University of Pittsburgh, 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.