Preview of Award 1812407 - Annual Project Report

Cover

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Project Title:	CAREER: Interconnected Mobile Computing in Wireless Networks
PD/PI Name:	Wei Gao, Principal Investigator
Recipient Organization:	University of Pittsburgh
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Submitting Official (if other than PD\PI):	Wei Gao Principal Investigator
Submission Date:	08/19/2020
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?**

Proliferation of mobile computing devices transforms the way people behave and access information in every aspect of their daily life. However, diverse manufacturing limits make current mobile devices far from ideal for being used anytime, anywhere. Instead, each device can only fit to a specific scenario. Traditional research strives to design individual mobile devices for different application scenarios by exploring tradeoffs among the various design perspectives, but cannot scale to the increasing complexity of future mobile applications and satisfy their requirements on the performance of mobile computing system.

The goal of this project is to develop key enabling technologies in wireless networks and mobile systems that realize Interconnected Mobile Computing (IMC). Instead of separately operating individual mobile devices, IMC fully interconnects multiple mobile devices owned by the same user via wireless networks, and allows these devices to complement each other via cooperative resource sharing. Hence, it fundamentally removes the physical boundary between devices and augments the mobile computing capability provided to user. The proposed research aims to ensure efficiency, adaptability and generality of IMC. First, we will design an extra communication channel in the wireless link that dedicates to resource sharing between mobile devices, hence minimizing the transmission latency of resource sharing and ensuring efficiency of IMC. Second, we will develop distributed network algorithms for resource sharing decisions, which adapt to frequent changes of network topology and maximize the efficiency of shared resource utilization. Third, a mobile middleware will be developed as the generic system interface to support mobile applications' remote access to shared system resources. The proposed designs will be implemented and evaluated over a medium-scale mobile testbed of software-defined radios and off-the-shelf mobile devices, and will also be validated by large-scale trace-based emulation.

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

Major Activities:

In this reporting period we have focused on developing advanced mobile computing and wireless networking techniques that allow transparent and prompt interconnection and interoperation between distributed mobile devices, so as to enable the key functionality of the proposed Interconnected Mobile Computing. More specifically, we first developed a unified OS framework that allow distributed mobile devices to remotely access the system resources of each other in a generalized manner. Furthermore, we develop wireless networking techniques to ensure that such remote resource access and operations can always be done with the minimum latency, even if the wireless channel is highly congested. Our research efforts also strive to allow these advanced wireless networking technologies to be deployed on commodity wireless devices, through a 100% software-defined approach without attaching extra hardware.

First, we aim to address the performance restriction of different types of mobile devices that are designed with respect to the requirements of different application scenarios. A viable solution to eliminate such restriction is to construct a personal mobile cloud, which incorporates and interconnects all the mobile devices owned by a user via wireless links. The major challenge of realizing such a personal mobile cloud is the heterogeneity of mobile computing devices, which resides in both hardware and software aspects and prevents these devices from being interconnected in a generic manner. The key to 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. To address these challenges, we design a mobile system framework to generically interconnect heterogeneous mobile devices towards a personal mobile cloud. Our basic idea is to develop the resource sharing framework as a middleware in the mobile OS, which exploits the existing mobile OS services to share resources between mobile devices.

Second, such interconnection and remote resource access may be delayed due to the wireless channel congestion on the air. Traditional wireless MAC protocols and cross-technology communication, however, are incapable of minimizing such delay when multiple wireless devices simultaneously interconnect. Instead, a better alternative is to avoid delay at the PHY layer by transmitting delay-sensitive IoT traffic through a dedicated wireless side channel, which operates over the spectrum being occupied but under-utilized by an existing wireless channel due to its in-band SNR margin: the main channel's SNR is usually higher than the SNR required to support the link data rate being used, due to discrete link rates and conservative rate adaptation. The major challenge of using a wireless side channel, however, is to support multiple access to the side channel from many IoT devices: The RF signal of the side channel, when being transmitted from multiple devices, will be appended to the main channel signal as extra interference and difficult to be correctly demodulated. The dynamic conditions of main channel may further result in intermittent availability or fluctuating amount of SNR margin, making it hard to allocate the SNR margin among multiple devices. To achieve such multiple accessibility, we design EasyPass, a new wireless PHY technique that realizes multiple access wireless side channels. EasyPass allows precise side channel demodulation via controlled asynchrony between transmissions of the side channel and the main channel. A side channel transmitter holds its transmission of each frame until the end of a main channel frame's preamble, which hence is not mixed with any side channel signal. This preamble, then, is used by the side channel to estimate the main channel's impulse response and remove the main channel signal from the mixed signal being received.

Third, another challenge of practically adopting the above wireless side channel design in practice is that, it requires modifying the PHY-layer wireless hardware, which are expensive when being applied to the large population of commodity devices or even impossible due to today's integrated system-on-chip (SoC) designs. The key insight of our work, instead, is that such new wireless signals could be emulated from a commodity MIMO-enabled wireless device, by controlling the individual payloads on its MIMO streams and mixing the transmitted wireless signals from these MIMO streams in the air. More specifically, most of wireless PHY operations on the time-domain signal could be represented as varying the signal's constellation point on the complex plane. These new constellation points, even mismatching any constellation diagram being used in existing wireless systems, can always be produced from a mixture of wireless signals in these existing systems with different amplitudes and phases. Based on this insight, we design StarLego, a wireless system that is potentially able to produce wireless signals with any arbitrary constellation point on the complex plane. The first step of StarLego is to convert the time-domain signal to be emulated to the corresponding constellation points via FFT, with respect to the number of MIMO streams being used. Afterwards, the core of StarLego is a payload emulation technique that decides the data payloads transmitted in each of the MIMO stream, in order to produce the desired constellation points when the transmitted signals are mixed in the air. From these new constellation points, StarLego can emulate custom time-domain signals, which could be either new PHY preambles or arbitrary data payloads.

Education Activities:

Some of the research results have been integrated with the education curricula at University of Pittsburgh. For example, the research outcome on achieving multiple-access low-latency wireless side channels (published at ACM CoNEXT 2019 and won the conference best paper) has been integrated into the curriculum of the course "ECE1175: Embedded Systems Design", towards multiple course projects for undergraduate students to practice their hands-on system building skills.

Outreach Activities:

The research outcome of this project has been applied to a broader scope of application scenarios, by exploring the potential of Interconnected Mobile Computing (IMC) to address the urgent societal needs. In particular, the PI is currently applying the developed IMC techniques to collaboration with pulmonary doctors in the Children's Hospital of Pittsburgh, to develop mobile systems that allow in-home self-evaluation of possible COVID-19 infections through commodity smartphones. This work has been reported by several news media internationally, such as WGN TV, Daily Mail, UK, Pittsburgh Post-Gazette, etc.

In addition, the PI has been actively involving minority and underrepresented groups of students into research. During the past year, he was supervising one female undergraduate student (Alana Dee) on mobile computing research, and also participated in the Hot Metal Bridge (HMB) program at Pitt, which offers a post-baccalaureate fellowship to minority students. He mentored several HMB fellows and introduced them to the research area of mobile and wireless networking.

Specific Objectives:

This project aims to satisfy the following requirements for IMC. Existing mobile computing systems, however, have been considered incapable of addressing the core challenges in satisfying these requirements.

1. Efficiency: IMC should be highly efficient without degrading mobile system performance. For example, the smartphone's remote GPS access should not incur any additional delay compared to local GPS access. This requirement motivates fundamental redesign of wireless networks, which currently have a much larger transmission latency compared to local execution time of mobile programs. Response time of mobile applications, hence, will increase when they access remote resources shared by others.

2. Adaptability: IMC should efficiently adapt to network and system dynamics, including user mobility, wireless channel fluctuations and mobile application behaviors. When the interconnection among mobile devices changes due to these dynamics, shared resources may become unavailable and IMC should be reconfigured accordingly, so as to avoid system performance degradation due to such resource unavailability and minimize additional system cost when switching to other shared resources. Such reconfiguration, however, is challenging due to the lack of centralized coordination among distributed devices.

3. Generality: Mobile devices should access the heterogeneous hardware and software resources shared by others via a generic suite of system interfaces, hence scaling to the increasing complexity of mobile systems. For example, the same interface should be applied for accessing GPS, body sensors and computational resources. Existing system designs, however, are limited to providing resource-specific interfaces.

In the last reporting period, we have been focusing on developing advanced mobile computing and wireless networking techniques to ensure the efficiency and generality of IMC under congested wireless connectivity across heterogeneous types of wireless devices. Furthermore, we also strived to allow these advanced wireless techniques to be adoptable at commodity wireless devices without PHY-layer hardware modification, through an approach of software-based packet emulation.

Significant Results:

We have designed and implemented a software-based framework, which could be inserted as a middleware in existing mobile OS (Android) and allow heterogeneous types of mobile devices to seamlessly interconnect and share system resources in a generalized manner. This implementation consists of less than 5,000 Lines of Codes (LoC) over various mobile platforms including smartphones, tablets and smartwatches, and demonstrated the efficiency of sharing various types of hardware (GPS, accelerometer, audio speaker, camera) between remote mobile devices. The evaluation results show that our design can efficiently support ubiquitous resource access between remote systems with arbitrary mobile applications accessing these resources, without incurring any significant system overhead. Our proposed framework is also fully compatible with existing application-level remote messaging protocols (e.g., MQTT and XMPP), and hence can also be efficiently exploited for mobile application development.

To our best knowledge, EasyPass is the first that allows multiple wireless devices to simultaneously transmit over a congested wireless link without being delayed or interrupted. First, EasyPass is highly adaptive. Side channel's operations always adapt to the available SNR margin and transmission patterns in the main channel, ensuring reliable data transmission even with strong noise or channel distortions. EasyPass well adapts to various network dynamics in channel conditions, device population and traffic demands, to flexibly allocate the available SNR margin among multiple wireless devices. Second, EasyPass is lightweight. A side channel in EasyPass uses the same channel detection, modulation and coding techniques as those in commodity wireless devices. It does not require any explicit coordination with the main channel or decode any main channel's transmitted data. No explicit coordination is required among side channel users, either. Hence, EasyPass incurs negligible computation and communication overhead. We implemented EasyPass over both USRP and WARP devices that operate on a 2.4GHz band. Our evaluation shows that EasyPass can reduce the transmission delay of multiple wireless devices by more than 90% over a highly congested 20MHz link, and also suppresses the delay jitter with heterogeneous network traffic patterns.

To the best of our knowledge, StarLego is the first that allows a commodity wireless device to enforce custom wireless PHY designs without any hardware modification, and it could greatly facilitate the penetration of new wireless PHY techniques to existing wireless systems. StarLego also advances the existing signal emulation schemes (e.g., WeBee and BlueBee) by being able to precisely produce new wireless signals with custom amplitudes and phases, and could potentially contribute to various application scenarios in emerging cross-technology communication. We verified the effectiveness of StarLego on producing custom wireless signals over WARP platforms, and demonstrated that StarLego can produce fine-grained constellation diagrams with negligible errors. Based on that, we further showcased the practical applicability of StarLego by implementing a custom WiFi PHY preamble over commodity WiFi PHY without hardware modification, and also developed techniques to prevent the commodity WiFi preambles from affecting correct signal emulation in StarLego.

The outcome of these research activities has also been actively applied to the university curriculum, as well as a collection of outreach activities. The PI has given multiple guest lectures to the minority student groups, by collaborating with the Pitt's Hot Metal Bridge (HMB) program. He was also mentoring several HMB fellows and involved them into the research activities of this project.

Key outcomes or Other achievements:

During the past year, the research outcome of this project has resulted in one journal paper and two conference papers.

The research work on developing a unified mobile computing framework for generic interconnections and resource sharing between remote mobile devices has been accepted for publication by IEEE Transactions on Mobile Computing, the best journal venue in the field of mobile computing. The research work on multiple access wireless side channels that minimizes the wireless delays in large-scale IoT networks has been accepted for publications by the 15th International Conference on emerging Networking EXperiments and Technologies (CoNEXT), one of the premier networking conferences, and won the Best Paper Award of the conference. The results of our work on allowing custom PHY-layer wireless designs to be applied on commodity mobile devices has been accepted for publication by the 21st International Workshop on Mobile Computing Systems and Applications (HotMobile), and this work could make important contributions to wide adoption of new wireless system designs to the large population of legacy wireless devices without expensive and complicated PHY-layer wireless hardware modification.

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

This project provided research opportunities to graduate students. The PI has been actively involving minority and underrepresented groups of students into research. During the past year,he was supervising multiple undergraduate students, including several ones from minority and underrepresented groups, on mobile computing and networking research. That includes multiple students from the Hot Metal Bridge (HMB) program at Pitt.

*** How have the results been disseminated to communities of interest? If so, please provide details.**

Our research work in this project has resulted in one journal paper and two conference papers. These publications will help people better understand our novel techniques on enabling interconnected mobile computing in wireless networks, and further apply these techniques to overcome the fundamental limitations on the wireless networking performance and local hardware resources of mobile devices.

The research outcome of this project has been applied to a broader scope of application scenarios, by exploring the potential of Interconnected Mobile Computing (IMC) to address the urgent societal needs. In particular, the PI is currently applying the developed IMC techniques to collaboration with pulmonary doctors in the Children's Hospital of Pittsburgh, to develop mobile systems that allow in-home self-evaluation of possible COVID-19 infections through commodity smartphones. This work has been reported by several news media internationally, such as WGN TV, Daily Mail, UK, Pittsburgh Post-Gazette, etc.

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

In the next reporting period, we plan to build on our existing designs of EasyPass and StarLego, to further extend these techniques to a wider collection of application scenarios where Interconnected Mobile Computing could significantly improve the system performance provided to the user. More specifically, we will investigate the possibility of realizing a wireless side channel over more challenging wireless networks, such as the cellular LTE networks or applications of multiple coexisting wireless networks. We will also strive to enhance the accuracy and efficiency of StarLego, by studying how to further allowing the emulated MAC-layer data payloads to be effectively calculated from user applications. These techniques will also be applied to various application scenarios, such as wireless sensing, mobile 360-degree video streaming, etc.

Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers

Haoyang Lu, Ruirong Chen and Wei Gao (2019). EasyPass: Combating IoT Delays with Multiple Access Wireless Side Channels. *Proceedings of the 15th International Conference on emerging Networking EXperiments and Technologies (CoNEXT)*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Ruirong Chen and Wei Gao (2020). StarLego: Enabling Custom Physical-Layer Wireless over Commodity Devices. *Proceedings of the 21st International Workshop on Mobile Computing Systems and Applications (HotMobile)*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Yong Li and Wei Gao (2019). Towards a Personal Mobile Cloud via Generic Device Interconnections. *IEEE Transactions on Mobile Computing*. . Status = AWAITING_PUBLICATION; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Licenses

Other Conference Presentations / Papers

Other Products

Other Publications

Patent Applications

Technologies or Techniques

Thesis/Dissertations

Websites or Other Internet Sites
Project website
http://www.pitt.edu/~weigao/reporting/career.html

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Gao, Wei	PD/PI	4

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: 4

Contribution to the Project: Lead the project.

Funding Support: This project

International Collaboration: No
International Travel: No

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?

Proliferation of mobile computing devices greatly extends the information that we can access anytime, and enables us to track, control and manage our bodies and the surrounding environment anywhere. The proposed research in this project aims at a complete rethink of how mobile computing systems are designed from the ground up, ranging from designs of wireless links and network algorithms to development of mobile system interfaces. We will study how potentials of heterogeneous mobile devices can be fully unleashed by being interconnected, so as to inspire novel theoretical and systematic studies that open up new research frontiers in emerging areas such as wearable computing and IoTs. If successful, such interconnection among mobile devices will provide a solid foundation to future development of pervasive and cognitive mobile applications, which persistently monitor human behavior and adaptively meet humans' needs.

Further, each task of the proposed research can potentially revolutionize wireless networking and mobile computing system designs. First, the extra wireless channel could greatly reduce the transmission latency of resource sharing and avoid degradation of mobile system performance. Second, distributed network algorithms that coordinate resource sharing and ensure efficient utilization of shared resources would greatly improve the efficiency and adaptability of mobile computing systems. Third, mobile system interfaces that support runtime access to heterogeneous remote resources are crucial to generality of IMC. The proposed techniques will have applications in a broader scope of cyber-physical systems such as industry control, remote sensing and connected healthcare by allowing seamless interconnection between disparate system components.

What is the impact on other disciplines?

The proposed research could be the critical factor to lay the foundation of realizing future large-scale smart connected systems, such as the Internet of Things. These smart systems, in turn, will serve as the key enabler of many cyber-physical systems, which will impact a large collection of different science and engineering disciplines. In particular, being able to precisely characterize the system instability and appropriately adapt to various types of system dynamics is critical to improve the mobile system efficiency and adaptability, and 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 Pittsburgh, by adopting many perspectives of the research results for undergraduate students' course projects and senior design topics. 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

During the past year, the PI originally planned to use this grant to support three PhD students for the Spring and Summer 2020 semesters. However, such student support and research expenditure were delayed and interrupted due to the COVID-19 pandemic. More specifically, two PhD students traveled overseas (back to China) during the 2019 winter break, and were then unable to return back to the US due to the COVID-19 pandemic and the subsequent US travel ban. As a result, they were unable to register for the Spring and Summer semesters, and Pitt policy hence disallows us to pay their stipends (when they are not in US). The third student, who started his PhD program in 2018, decided to quit the PhD program in December 2019. The PI tried to find a replacement within the ECE Department, but was unsuccessful due to the COVID-19 pandemic that stopped the majority of research activities and departmental operations in the Spring and Summer 2020 semesters.

During the remaining period of this project, the PI will strive to make sure that the proposed research agenda is fully executed as planned and the remaining budget on this grant is effectively spent. The PI is confident in the effectiveness and timeliness of the research progress and expenditure in the upcoming AY, because the well-prepared Pitt reopening plan will be able to effectively resume most of research and teaching activities in Fall 2020, thus ensuring effective student recruitment and payrolls. More specifically, the PI proposes a detailed spending plan (in the attached supporting document) for the following two years (including an one-year grantee-approved no-cost extension). Some explanations about the spending plan are as follows:

1. The available budget ($443,463) is based on the Pitt's July level report that I just received today, plus the increment for the next FY.

2. Based on the Pitt's policy, the tuition of any fully supported student will be 100% covered by the university. Instead, the university will charge 50% fringe for the student stipends being paid. In the spending plan, the PI plans to pay the graduate students $2,400/mo in the AY 2020-2021 and $2,500/mo in the AY 2021-2022.

Changes that have a significant impact on expenditures

See above. The delay in PhD student recruitment has also delayed the project's expenditure.

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.

Special Requirements

Responses to any special reporting requirements specified in the award terms and conditions, as well as any award specific reporting requirements.
Nothing to report.

Supporting Files

Filename	Description	Uploaded By	Uploaded On
spending plan.pdf	The proposed spending plan for the remaining two years of the project (including the one-year grantee-approved no-cost extension).	Wei Gao	08/19/2020