My Desktop
Prepare & Submit Proposals
Prepare and Submit Proposals
(Limited proposal types)
Demo Site: Prepare Proposals
Prepare Proposals in FastLane
Proposal Status
Awards & Reporting
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# Preview of Award 1812407 - Annual Project Report

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## Cover

| | |
|---|---|
| Federal Agency and Organization Element to Which Report is Submitted: | 4900 |
| Federal Grant or Other Identifying Number Assigned by Agency: | 1812407 |
| Project Title: | CAREER: Interconnected Mobile Computing in Wireless Networks |
| PD/PI Name: | Wei Gao, Principal Investigator |
| Recipient Organization: | University of Pittsburgh |
| Project/Grant Period: | 09/01/2017 - 06/30/2022 |
| Reporting Period: | 07/01/2020 - 06/30/2021 |
| Submitting Official (if other than PD\PI): | N/A |
| Submission Date: | N/A |
| Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions) | N/A |

## 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 and objectives (you must provide information for at least one of the 4 categories below)?**

Major Activities:

During the past year, we are striving to apply our developed IMC techniques to a large variety of different computing applications, in particular, mobile and connected health applications, as part of University of Pittsburgh's response to the COVID-19 pandemic from the academic sector. More specifically, the following research activities have been made.

First, we made research efforts to allow accurate, convenient and low-cost spirometry tests at home by patients themselves, using commodity smartphones. This capability would be useful to dramatically alleviate the burden of public healthcare system with the burst of patient needs, and hence make important contributions to combating the COVID-19 pandemic. Spirometry, as the most commonly used pulmonary function testing (PFT), assesses such obstruction by measuring the volume and velocity of breathing airflow, and is crucial in pulmonary disease evaluation and monitoring. Ideally, spirometry should be daily conducted out of clinic, to timely detect and avoid frequent disease exacerbations that cause emergency department visits or hospitalizations. However, current spirometers in clinic are too bulky for daily home use. Recent efforts reduce the size of spirometers but their costs (>$2,000) are still too high for home use. Low-cost spirometers priced at <$100 are mostly inaccurate and could produce >20% error. To reduce the cost of portable spirometers without impairing the PFT accuracy, researchers developed wearable sensing systems, but required attaching extra hardware to human bodies. We developed a new technique called SpiroSonic, a novel system design that uses commodity smartphones to support complete, accurate yet reliable spirometry tests out of clinic, with various environmental and human factors. Our design builds on the close correlation between lung function and chest wall motion of humans, which has been widely validated in clinical practice. SpiroSonic measures chest wall motion as an externally observable biomarker, and interprets such motion into lung function indices. To measure such motion, SpiroSonic transmits ultrasound signal with the smartphone's speaker, and analyzes the signal being reflected by the patient's chest wall and received by the smartphone's microphone. In this way, SpiroSonic is 100% contactless and non-intrusive.

Second, we have also applied the IMC techniques onto another healthcare problem – the muscle fatigue, which is common among humans and also a crucial indicator of many muscular diseases such as muscular dystrophy and disorders. During clinical visits, the muscle fatigue can be evaluated by lactic acid accumulation using a blood test or myoelectric signals using electromyography (EMG), but frequent daily evaluation of muscle fatigue out of clinic is usually preferred in most of muscular disease diagnosis for long-term tracking of disease progress and medication efficacy. Unfortunately, effective methods for such out-of-clinic evaluation are currently missing, and patients instead are only asked to self report their feelings of fatigue by completing certain questionnaires. To address this challenge, we developed MyoMonitor, a new technique that uses commodity smartphones for objective muscle evaluation out of clinic. This technique is built on the physiological fact that human muscles will unconsciously tremble or shake when getting fatigued and such tremor proportionates to the level of muscle fatigue. Since this muscle tremor can produce shape changes on the muscle

surface, we could measure the muscle fatigue from such changes which affect the acoustic signal being transmitted between the smartphone's built-in speaker and microphone. In practice, to ensure the accuracy and reliability of evaluating muscle fatigue, our design aims to address multiple technical challenges, including 1) As the built-in speakers of commodity smartphones are usually omnidirectional, the transmitted acoustic channel is significantly affected by the motions of other parts of the human body (e.g., head and hands); 2) We need to appropriately interpret the disturbances on the acoustic channel into quantified levels of muscle fatigue, so that we have numerical metrics of fatigue level for fatigability analysis..

Third, we have been using the IMC techniques to investigate the possible security vulnerabilities on commodity smartphones, due to their rich sensing modularities being provided. More specifically, we developed MagHacker, a new sensing system that can eavesdrop mobile users' handwriting inputs using stylus pens from commodity smartphones. The basic rationale of such security vulnerability is that the movement of stylus pen's internal magnet changes the nearby magnetic field. This change could be captured by a smartphone's on-board magnetometer and analyzed to infer the handwriting. Compared to existing methods of eavesdropping attacks that retrieve and analyze the IMU data from the victim's on-body devices, this new attack can be reliably launched from remote without compromising the victim's personal mobile devices. Our system assumes that the victim writes in English and aims to recognize each individual English letter of his/her handwriting from distance. Being different from existing work on magnetic sensing that uses multiple custom magnetometers to track the magnet's 3D position, MagHacker only uses the readings from a single magnetometer on the commodity mobile device operated by the attacker, and requires no extra hardware. To ensure accuracy, MagHacker divides the continuous magnetometer readings into small segments, each of which corresponds to a letter being written and is individually recognized. This segmentation, however, is challenging because of the heterogeneous efforts to write different letters, which make it hard to estimate the duration of writing each letter. Instead, MagHacker exploits the fluctuation of humans' speed of hand movement in writing, which changes less frequently in transition between letters. MagHacker calculates the victim's speed of hand movement from magnetometer readings and applies Continuous Wavelet Transform (CWT) to the time series data of movement speed. The produced spectrogram, then, represents the frequency of speed changes and can be used for segmentation.

Education Activities:

Some of the research results have been integrated with the education curricula at University of Pittsburgh. For example, the research outcome on supporting spirometry tests on commodity smartphones (published at ACM MobiCom 2020) 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 developed mobile systems have been applied into clinical practice for pulmonary disease evaluation and monitoring, and contribute to combating against the COVID-19 pandemic. 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 applying the developed IMC techniques to a wide variety of practical computing application scenarios, in particular, the smart and connected healthcare applications. More specifically, we have been using the IMC techniques to support accurate and low-cost spirometry tests for pulmonary disease evaluation on commodity smartphones, and to support convenient muscle fatigue evaluation on commodity mobile devices. We have also been striving to explore the possible security vulnerabilities, enabled by the extra computing capabilities of IMC.

Significant Results:

First, we have implemented the SpiroSonic design on commodity smartphones. To our best knowledge, SpiroSonic is the first spirometry system using commodity smartphones in regular home settings. It provides a convenient yet cost-free tool for continuous tracking and evaluation of pulmonary diseases, which are crucial to patients' wellbeing. It also contributes to early-stage diagnosis of COVID-19 out of clinic, and helps reduce the burden of public healthcare system in pandemic. The key characteristics of SpiroSonic are as follows: 1) SpiroSonic is accurate. Its error of

measuring chest wall motion is constrained within 4mm. When being evaluated among healthy humans, its error of lung function monitoring is always lower than 3%. 2) SpiroSonic is adaptive. It can precisely remove the impact from various environmental and human factors, and allows flexible variations of smartphone's position (up to 20cm) and orientation (up to 30-degree tilting) during spirometry tests without impairing the accuracy. It also well adapts to humans' body conditions, as well as different types of clothes being worn. 3) SpiroSonic is lightweight. It is contactless and does not require any extra hardware. It consumes <15% of smartphone's battery life with 1-hour usage. 4) SpiroSonic is easy to use. It is implemented as an Android app, and its spirometry tests are fully automated and require the minimum involvement from users. Furthermore, by collaborating with clinical pulmonologists and biostatisticians, we conducted a clinical study in the Children's Hospital of Pittsburgh of 4 months, over 83 pediatric patients that cover different ages, genders, body conditions and diseases. With the IRB approval, all studies were done in clinical rooms when patients visited the hospital for spirometry tests, and 281 data records from tests are collected. Results of our clinical study are as follows: 1) SpiroSonic's error of lung function monitoring is between 5% and 10% for most patients. Since the error of in-clinic spirometry is around 5%, results from SpiroSonic could be reliably used as clinical evidence. 2) We statistically demonstrate that patients' chest wall motion is strongly correlated to their lung function indices, and some of such correlations are linear. 3) SpiroSonic achieves high monitoring accuracy over different patient subgroups, divided by age, gender and disease. It is hence widely applicable to the large population of patients.

Second, we have implemented our MyoMonitor system design as an Android smartphone app, which uses 20 kHz as the carrier wave of our encoded signal. Though commodity smartphones usually have two pairs of speaker and microphone for music playback or voice call, we choose top speaker along with bottom microphone because this combination can ensure the best results of channel estimation from our experiments. To minimize interaction needs, the subject only needs to signal the start and end of each test by pressing a phone volume button. The test protocol is suggested by clinicians based on a simple bicep workout and entire procedures are automated by voice and screen instructions. The protocol stipulates that the basic unit of our test is a group, in which we require the subject to complete as many biceps workouts as possible until he(she) feels hard to follow the speed of voice instructions. Each workout includes steps of preparation, lift-up, hold, lift-down and a resting interval for the following workouts. By explicitly defining the duration of these steps and the elevation that the dumbbell should be lifted, we make the protocol standardized so that people with different muscle condition should have similar feeling of fatigue after enough times of workout. By collaborating with orthopaedic doctors, we devised a protocol of monitoring biceps brachii fatigue. The protocol is instructed by a fully automated smartphone app with voice guidance. We conducted experiments over five student volunteers with more than 200 groups of workouts in total. 70% of the data can exhibit the expected results and consistency of fatigue evaluation. Our preliminary exploration of the technique paves the way for further clinical investigation and validation, which could be a potentially beneficial tool for patients with muscle myopathy and disorders.

Third, we have implemented and tested MagHacker over a wide collection of commodity mobile devices (e.g., Apple iPhone Xs and Google Pixel 2 XL smartphones) and stylus pen products (e.g., Microsoft Surface Pen, Adonit Snap 2 Pen and Maglus Pen), and evaluated the eavesdropping performance of MagHacker with five student volunteers who handwrote all the possible combinations and transitions of English letters. From our experiment results, we have the following conclusions: 1) MagHacker is highly accurate. MagHacker can correctly recognize more than 80% of lowercase and uppercase letters being written by all experiment participants, with different writing

patterns and habits. 2) MagHacker is highly adaptive. MagHacker can well adapt to the heterogeneous writing speeds of humans, and can achieve good accuracy of eavesdropping over different stylus pen models. It can also retain the accuracy of eavesdropping in different environmental conditions, even with nearby metal objects. 3) MagHacker is widely applicable. MagHacker allows the attacker to effectively eavesdrop within the physical proximity of the victim, and achieve good accuracy with an eavesdropping distance up to 20cm. It also incurs the minimum power consumption on the attacking device and hence allows several hours of continuous eavesdropping.

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 and implementing SpiroSonic, a new mobile system that supports spirometry tests on commodity smartphones, has been accepted for publication by ACM MobiCom 2020, the best conference for mobile computing and networking. The research work on developing MyoMonitor that supports muscle fatigue evaluation on commodity smartphones has been accepted for publication at the Elsevier Smart Health Journal. The research work on MagHacker, a new sensing system that allows eavesdropping of mobile users' handwriting inputs with stylus pens, has been accepted for publication by ACM MobiSys 2020, the best conference in mobile computing systems.

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

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

*** 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, and further apply these techniques to overcome the fundamental limitations on the wireless networking performance and local hardware resources of mobile devices. 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?**

In the next reporting period, we plan to follow up on our current research activities, and further explore how the IMC techniques could be utilized to enhance the performance of mobile computing applications in a broader context. More specifically, we will explore the possibility of collaborative computation across multiple mobile devices in an integrated IMC system, when they are being applied smart healthcare applications with distributed data sources from multiple patients. In addition, we will also strive to develop technical solutions to better protect the users' data privacy in such distributed and collaborative computing scenarios.

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## Products

**Books**

**Book Chapters**

**Inventions**

**Journals or Juried Conference Papers**

Xingzhe Song, Boyuan Yang, Ge Yang, Ruirong Chen, Erick Forno, Wei Chen and Wei Gao (2020). SpiroSonic: Monitoring Human Lung Function via Acoustic Sensing on Commodity Smartphones. *in Proceedings of the 26th International Conference on Mobile Computing and Networking (MobiCom)*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Xingzhe Song, Hongshuai Li and Wei Gao (2021). MyoMonitor: Evaluating Muscle Fatigue with Commodity Smartphones. *Elsevier Smart Health*. 19 (100175), . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed =

Yes

Yihao Liu, Kai Huang, Xingzhe Song, Boyuan Yang and Wei Gao (2020). MagHacker: Eavesdropping on Stylus Pen Writing via Magnetic Sensing from Commodity Mobile Devices. *in Proceedings of the 18th ACM International Conference on Mobile Systems, Applications, and Services (MobiSys)*. . Status = PUBLISHED; 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

On this project website, we provide details regarding this specific project (personnel, papers, software, etc.).

## Participants/Organizations

**What individuals have worked on the project?**

| Name | Most Senior Project Role | Nearest Person Month Worked |
|---|---|---|
| Gao, Wei | PD/PI | 4 |
| Huang, Kai | Graduate Student (research assistant) | 3 |
| Song, Xingzhe | Graduate Student (research assistant) | 4 |
| Yang, Boyuan | 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:** 4

**Contribution to the Project:** Lead and supervise the project.

**Funding Support:** This project

**Change in active other support:** No

**International Collaboration:** No
**International Travel:** No

**Kai Huang**
**Email:** k.huang@pitt.edu
**Most Senior Project Role:** Graduate Student (research assistant)
**Nearest Person Month Worked:** 3

**Contribution to the Project:** Involved in experimentation of both the MagHacker and SpiroSonic systems

**Funding Support:** This project

**International Collaboration:** No
**International Travel:** No

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**Xingzhe Song**
**Email:** x.song@pitt.edu
**Most Senior Project Role:** Graduate Student (research assistant)
**Nearest Person Month Worked:** 4

**Contribution to the Project:** Design and implement the systems of SpiroSonic and MyoMonitor

**Funding Support:** This project

**International Collaboration:** No
**International Travel:** No

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**Boyuan Yang**
**Email:** by.yang@pitt.edu
**Most Senior Project Role:** Graduate Student (research assistant)
**Nearest Person Month Worked:** 3

**Contribution to the Project:** Be responsible for the implementation and evaluation of the SpiroSonic system.

**Funding Support:** This project

**International Collaboration:** No
**International Travel:** No

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

**Were other collaborators or contacts involved? If so, please provide details.**
Nothing to report

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## 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 project has supported three PhD students working on their dissertation. 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 was the impact on teaching and educational experiences?**
Nothing to report.

**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.

**What percentage of the award's budget was spent in a foreign country?**
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.

**Change in primary performance site location**
Nothing to report.

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## 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.