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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 - 06/30/2021
Reporting Period:	07/01/2018 - 06/30/2019
Submitting Official (if other than PD\PI):	Wei Gao Principal Investigator
Submission Date:	05/17/2019
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:

Based on the previous research accomplishments made by this project, in this reporting period we have further focused on developing advanced wireless networking techniques that ensure ultra-low transmission latency for traffic of data and resource sharing among heterogeneous types of connected mobile devices. Ensuring such ultra-low transmission latency, as stated in the proposal, is crucial to the efficiency of interconnected mobile computing. Based on these techniques, we further applied the concept of interconnected mobile computing to the emerging field of Virtual Reality (VR), and strived to ensure high-performance VR over resource-constrained mobile computing devices (e.g., smartphones) by efficiently leveraging the proximate computing power of edge cloud through low-latency wireless links.

First, we further extended our previous work on minimizing the wireless transmission delay over a highly congested wireless channel, by building a high-throughput side channel over the same spectrum that is currently occupied but under-utilized by an existing wireless channel. In order to provide sufficient throughput for this side channel, our work exploits the unique properties of modern digital modulation methods, such as OFDM, and encodes data as patterned interference by erasing the energy of specific subcarriers in the main channel's OFDM symbols. Since such energy erasure does not increase the RF transmit power, it can be used to encode data into every OFDM symbol in the main channel, hence dramatically increasing the side channel throughput. On the other hand, since OFDM modulates data into separate subcarriers in both time and frequency domains, the amount of patterned interference could be efficiently controlled by interfering only a small portion of OFDM subcarriers, without affecting main channel decoding and its resistance to channel contention.

Second, we also applied this technique of per-subcarrier energy erasure to enabling cross-technology coexistence for extremely weak wireless devices, which has intermittent power supply from energy harvesting and hence cannot afford any extra data transmission or signal processing delay that may results in missing transmission opportunities. To offload such extra delay from these weak devices, 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. For example, strong wireless devices use WiFi to achieve high channel bandwidth, (>20Mbps) by using complicated modulation schemes, channel coding techniques and higher transmit power. ZigBee, on the other hand, is usually used by weak wireless devices to minimize the power consumption using a narrowband channel (2MHz) with simplified modulations (OQPSK). Motivated by such diversity, we adaptively adjust the wireless technology operated by strong wireless devices to reserve a minor portion of its spectrum, for the wireless channel operated by weak devices. In this way, we allow any wireless traffic from weak devices to be transmitted concurrently with that from strong devices, without any modification on wireless operations at weak devices.

Third, we were actively seeking to apply these advanced wireless techniques to support emerging application scenarios of Interconnected Mobile Computing, in particular, supporting high-performance VR over resource-constrained mobile devices. To address such resource constraints, a viable solution is to offload the computationally expensive

VR frame rendering to the nearby edge cloud, which then wirelessly transmits the rendered frame data back to the mobile HMD. The edge cloud nowadays, however, could be usually located over individual households with end-user desktop PCs or small-scale workstations, which have much lower capacities in both computation and communication compared to traditional cloud facilities such as data centers. They, hence, fail to provide satisfactory VR performance when serving multiple VR users in a household at the same time (e.g. multiple family members play the same multi-player VR game). Our solution to such excessive workload on the edge cloud builds on experimental observations from real VR applications, which indicate the VR frames being rendered and transmitted for different users as highly redundant. Based on these observations, we designed the Multi-User Virtual Reality (MUVR) system, a systematic mobile VR framework that maximizes the efficiency of edge cloud's resource utilization to support multi-user VR. The key approach of MUVR is to adaptively reuse the previous results of VR frame rendering whenever necessary, by identifying and exploiting the aforementioned redundancy when the edge cloud renders VR frames and transmits these frames to the mobile HMD. In particular, MUVR eliminates redundant computations in VR frame rendering via frame memoization, which caches the invariant background view of rendered VR frames. These caches will be opportunistically reused when rendering frames for other users in the future, if they are at the similar camera locations in the virtual world.

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 Pittsburgh. For example, the research outcome on ultra-low-latency wireless networking and systematic techniques on supporting mobile VR has been integrated into the curriculum of the course "ECE1160/2160: Embedded Computer System Design 1", towards multiple course projects for undergraduate students to practice their hands-on system building skills.

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 PHY-layer wireless techniques to ensure the efficiency of IMC under congested wireless connectivity across heterogeneous types of wireless devices. Furthermore, we also strived to enhance the generality of IMC by applying its concept and techniques to emerging mobile computing scenarios, such as VR.

Significant Results:

We have extended our previous design of high-throughput wireless side channel, and implemented our design over custom wireless hardware platform, the WARP v3 software-defined radio boards. Doing so allows our implemented prototype to be able to efficiently communicate with the commodity wireless hardware such as off-the-shelf smartphones and smartwatches, as well as extensive experimentation with these commodity devices. Our experiments show that our system can provide a side channel throughput of up to 2.5 Mbps, which is 10 times higher than existing work with minimal impairment to the main channel performance. It also reduces the delay in commodity 802.11 networks by up to 90%, and significantly eliminates the chance of delay jitters in such networks. Such delay reduction and throughput enhancement enable many delay-sensitive mobile applications, e.g. Skype, to operate in the side channel without any performance degradation even if the main channel is highly congested. The traffic from these applications, meanwhile, can be supported by the side channel without impairing the main channel performance.

We further applied this technique of per-subcarrier energy erasure being used in the side channel towards cross-technology coexistence, by intentionally reserving certain spectrum for the weak wireless devices to use without any active signal processing. This design, however, is challenging when being applied to WiFi and ZigBee because of i) the difficulty of precisely and efficiently recognizing weak ZigBee signal from an incompatible strong WiFi device and ii) the possible performance loss at coexisting wireless technologies. To precisely detect the weak ZigBee packets from a strong WiFi device, one straightforward approach is to analyze the wireless channel with Fast Fourier Transform (FFT), but it introduces computationally overhead and additional response latency. Instead, we exploit the different frequency offsets in WiFi and ZigBee channels to probabilistically decide whether a wireless signal is produced by WiFi or ZigBee. It further improves the accuracy of such decisions to 93% using statistical channel information, without requiring any coordination across different wireless technologies. Based on such decisions, our approach flexibly schedules such spectrum reservation over time, so as to utilize the ZigBee's built-in error correction capabilities for minimum packet reception errors.

When applying these wireless techniques to mobile VR applications between resource-constrained mobile devices and the edge cloud, we are able to significantly improve the mobile VR performance by identifying and reusing the redundant system computations. Even in highly dynamic VR scenarios such as interactive games, our experimental studies show that movement trajectories of different VR users share more than 30% in common when they are near the same Points of Interests (PoIs) in the VR world. Such locality in VR user movements leads to redundant frames with very similar scene views across different users. Second, consecutive frames of the same VR user are also correlated, because of the perspective object projection in VR applications that reduces the impact of user movement on the user view. We verified that such redundancy could exceed 50%, i.e., more than half of pixels in these frames are identical with each other. Based on these observations, our proposed MUVR framework could efficiently reuse these redundant computation results. We have implemented MUVR over the Android OS and Unity VR application engine as a mobile middleware between VR applications and OS drivers, so as to ensure its generality over different VR applications with heterogeneous dynamics and computation demands. More specifically, MUVR is implemented in native language within the Android OS, and we utilize the unified OpenGL APIs for graphics operations such as VR frame rendering, so as to tackle the heterogeneity of shading languages and scripting APIs used by different VR applications. The implementation consists of ~5,000 Lines of Codes (LoC) in total, and

our experimental results over real-world VR applications show that MUVR, when being used to simultaneously serve multiple (>4) VR users, could efficiently reduce the computation burden at the edge cloud by more than 90% with complicated scenes and intensive user movement, while reducing more than 95% of the VR frame data being wirelessly transmitted.

Key outcomes or Other achievements:

The results of our work “Minimizing Wireless Delay with a High-Throughput Side Channel”, has been accepted for publication by *IEEE Transactions on Mobile Computing*.

The results of our work “Enabling Cross-Technology Coexistence for Extremely Weak Wireless Devices,” has been accepted by the highly competitive *IEEE Conference on Computer Communications (INFOCOM 2019)*, which has an acceptance ratio of 19.7%.

The results of our work “DeltaVR: Achieving High-Performance Mobile VR Dynamics through Pixel Reuse,” has been accepted by the highly competitive *ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN 2019)*, which has an acceptance ratio of 26.8%.

The results of our work “MUVR: Supporting Multi-User Mobile Virtual Reality with Resource-Constrained Edge Cloud,” has been accepted by the highly competitive *ACM/IEEE Symposium on Edge Computing (SEC 2018)*.

The source codes of the hardware prototyping and software systems in these papers have been made online at: https://github.com/utkmsnl.

*** 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 top-tier journals and various academic conferences.

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

Our research work in this project has resulted in one journal paper and three 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. 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 year, we will build on our existing techniques and further strive to broaden the scope to which the IMC techniques could be applied. More specifically, we plan to leverage and expand the existing techniques of wireless packet emulation, so as to allow emulating any arbitrary wireless waveforms. The outcome of this capability will allow traditional wireless devices with old access technologies to be fully compatible with the new generations of wireless technologies, so as to greatly enhance the connectivity among heterogeneous types of wireless devices and the computing capability enabled by such interconnection.

We also plan to synergistically integrate the concept of IMC with the emerging research of edge computing, and use the developed wireless techniques to better connect different tiers, components and elements at the network edge, towards more adaptive and generic mobile computing models. On the other hand, having realized the potential cyber-security threats brought by the interconnectivity among mobile devices, we will also strive to develop systematic security solutions to protect the sensitive data and services of mobile users.

Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers
Ruirong Chen and Wei Gao (2019). Enabling Cross-Technology Coexistence for Extremely Weak Wireless Devices. *Proceedings of the 38th IEEE Conference on Computer Communications (INFOCOM)*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Ruirong Chen, Haoyang Lu and Wei Gao (2019). Minimizing Wireless Delay with a High-Throughput Side Channel. *IEEE Transactions on Mobile Computing*. . Status = AWAITING_PUBLICATION; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Yong Li and Wei Gao (2018). MUVR: Supporting Multi-User Mobile Virtual Reality with Resource Constrained Edge Cloud. *Proceedings of the 3rd ACM/IEEE Symposium on Edge Computing (SEC)*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Yong Li and Wei Gao (2019). DeltaVR: Achieving High-Performance Mobile VR Dynamics through Pixel Reuse. *Proceedings of the 18th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN)*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Licenses

Other Conference Presentations / Papers

Other Products

Other Publications

Patents

Technologies or Techniques

The source codes of the software systems and hardware prototyping developed in this project have been released to the public at: github.com/utkmsnl

Thesis/Dissertations

Websites
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	2
Chen, Ruirong	Graduate Student (research assistant)	3
Li, Yong	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: 2

Contribution to the Project: Serving as the PI who leads and manages the project.

Funding Support: This project

International Collaboration: No
International Travel: Yes, Canada - 0 years, 0 months, 5 days; - 0 years, 0 months, 0 days; - 0 years, 0 months, 0 days

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Ruirong Chen
Email: ruc28@pitt.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Developed PHY-layer wireless techniques to realize the high-throughput wireless side channel and

Funding Support: This project.

International Collaboration: No
International Travel: Yes, France - 0 years, 0 months, 6 days

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Yong Li
Email: yli118@vols.utk.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Applied the wireless techniques to improve the interconnectivity between mobile devices and the edge cloud in mobile VR application scenarios.

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 project has supported two 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. In addition, the outcome of the proposed research has been turned into several course projects in undergraduate and graduate classes, and have been found very useful by the students to train their hands-on system building skills and get well prepared for their future career.

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

Since the PI moved from University of Tennessee to University of Pittsburgh in 2017, there is a resulted lapse in transferring this research grant, transferring the PI's research program, and recruiting new PhD students between the two institutions. As a result, there is a delay in research expenditures of this grant. In the remaining periods of this project, the PI plans to expand his research program at Pitt, by recruiting more PhD students and speed up the progress of research and expenditure in this project.

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.