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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:	07/01/2017 - 06/30/2018
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 (you must provide information for at least one of the 4 categories below)?**

Major Activities:

This project outlines a career development plan addressing the fundamental challenges of IMC. Its research plan spans the network and system technologies that are vital to efficient, adaptable and generic interconnection among mobile devices. To efficiently address these fundamental challenges of IMC and satisfy the key requirements of IMC in practical wireless network scenarios, we had the following major activities in the past year.

First, we developed a lightweight and practical wireless PHY technique, named vMod, that is able to maximize the wireless network throughput under severe channel conditions, by redesigning the wireless link rates from discrete to continuous. This work is motivated by the discrete link rates being used in current wireless networks, which result in significant gap between consecutive link rates and low efficiency of spectrum utilization: a wireless link operates at the same data rate before the channel quality reaches the requirement of the next higher rate. The network throughput during the meantime, then, remains constant and may be much lower than the momentary channel capacity. To address this limitation, 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 idea of vMod is to modulate a fractional number of data bits into each symbol by employing the Variable-Length Code (VLC), which is able to statistically yield any link rate. vMod does not produce any redundant data transmission, and hence retains the power efficiency of current wireless networks. Besides, vMod's demodulation over each symbol is independent and only involves demapping from a constellation point to data bits. It hence incurs 10x less overhead compared to rateless codes. We implemented vMod over USRP with GNURadio toolkit. 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 compared to existing rateless codes. vMod, hence, could be easily integrated with other advanced wireless techniques, such as channel bonding and MIMO, to achieve much higher improvement of wireless throughput.

Second, we aim to fully interconnect the multiple types of mobile computing devices owned by a mobile user towards an integrated personal mobile cloud, so as to allow these devices to complement each other via cooperative resource sharing. To overcome the heterogeneity of these computing devices, 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. These services hide the low-layer details of device driver operations while providing unified data access APIs to user applications. Interconnection between mobile devices, then, could be realized via remote access and invocation of these OS services. Since these services are executed as a standalone system process by the OS kernel and are separated from application processes, remote service invocation can be done via inter-process communication (IPC) between mobile systems without involving complicated issues such as memory referencing and synchronization. As a result, any new device can be incorporated into the mobile cloud by inserting our framework into its OS, without modifying the OS kernel, our framework itself, or the source code of any mobile

application. We have implemented our design on Android OS with 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.

Education Activities:

Two PhD students have worked on the project. Some of the research results have been integrated with the education curricula at University of Tennessee Knoxville and University of Pittsburgh. For example, techniques of interconnecting heterogeneous mobile devices have been added to the contents of our undergraduate course “ECE1161: Embedded Computer System Design 2”, and provided the students with the opportunity of working with the Android OS and off-the-shelf mobile devices.

Specific Objectives:

The proposed research 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.

Significant Results:

We have developed new PHY modulation techniques, named vMod, that can transform 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 idea of vMod is to modulate a fractional number of data bits a data symbol that contains an integer number of constellation points. To do this, we 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. For example, by splitting the bitstream with a VLC of 4-bit and 5-bit codewords, we can achieve any link rate between 24 Mbps and 30 Mbps (with a 1/2 code rate), by adjusting the ratio between 4-bit and 5-bit codewords

in the VLC. Such granularity of continuous link rates could be further improved by combining vMod with the existing variety of code rate options.

Furthermore, We ensure the generality and power efficiency of vMod by exploiting the modules in existing wireless systems whenever possible. First, we build our VLC by extending the fixed-length code being used in existing systems, and construct new constellation diagrams for modulation by mapping the new variable-length codewords to the unused signal positions in existing QAM constellations. In this way, we ensure that any link rate could be achieved by the same generic approach with the minimum wireless transmit power. Second, information about the lengths of VLC codewords carried by symbols is the key to correct demodulation. To convey such information without impairing throughput, we transmit both regularly modulated and VLC-modulated symbols in the same wireless link, so that such information can be indicated by the permutation of how these two types of symbols alternatively appear. The design of vMod has been published at IPSN 2018.

We also developed a generic application framework that allows heterogeneous mobile computing devices to generically share their local hardware resources with each other. In general, our framework intercepts the requests of resource access generated from local mobile applications, and forwards these requests to another remote mobile device which acts as the server and provides the shared resource. Every time when a resource access request is received, the server will invoke its local OS service corresponding to the requested resource, and reply with the resource data. Our framework supports resource access between mobile devices in two ways: proactive invocation and reactive callback. First, when a remote system service is available, a service proxy object will be created by our framework to initiate the IPC between the client and the server. In proactive invocation, every time when an application requests to remote service access, the proxy object at the client triggers a remote invocation event, which is captured at the server to invoke the corresponding service method. Second, applications can also access system resources reactively by receiving data in system events, e.g., location update. Resource access in this case is handled by reactive callbacks, which allow applications to register and listen to a system event with a callback handle. This handle is called via a callback proxy by the service at the server when the system event occurs, and then used to transmit resource data back to the client. This invocation procedure is similar to proactive invocation, but in a reverse direction. This design has been published at INFOCOM 2017.

Key outcomes or Other achievements:

The results of our work “Continuous Wireless Link Rates for Internet of Things,” has been accepted by the highly competitive *ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN 2018)*, which has an acceptance ratio of 26.8%.

The results of our work “Interconnecting Heterogeneous Devices in the Personal Mobile Cloud,” has been accepted by the highly competitive *IEEE Conference on Computer Communications (INFOCOM 2017)*, which has an acceptance ratio of 20.9%.

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

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

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

Our research work in this project has resulted in two conference papers. These publications will help people better understand our novel techniques on 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 investigate techniques to satisfy the requirements of efficiency and adaptability in IMC. First, we plan to further extend our wireless PHY layer design to allow concurrent wireless transmissions from heterogeneous types of wireless radios (e.g., WiFi, ZigBee, Bluetooth, etc), without impairing the performance of any transmission. This requires fundamental rethink about how the wireless PHY will operate to utilize the limited spectrum. Second, we will further apply our IMC framework towards specific application domains. More specifically, we will explore the possibility of improving the performance of Virtual Reality over resource-constrained mobile devices via such generic resource sharing between mobile devices and the cloud. We will also exploit such interconnectivity to facilitate the enforcement of various cybersecurity solutions.

Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers

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

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

Licenses

Other Conference Presentations / Papers

Other Products

Other Publications

Patents

Technologies or Techniques

Thesis/Dissertations

Websites

Project website
http://www.pitt.edu/~weigao/reporting/career.html

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Gao, Wei	PD/PI	3
Li, Yong	Graduate Student (research assistant)	6
Lu, Haoyang	Graduate Student (research assistant)	6

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: Supervise and manage the project

Funding Support: this project

International Collaboration: No
International Travel: No

Yong Li
Email: yli118@vols.utk.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: Design and implement the generic resource sharing framework that interconnects heterogeneous mobile computing 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: 6

Contribution to the Project: Design and implement vMod, a wireless PHY technique that maximizes the link throughput under severe channel conditions

Funding Support: This project

International Collaboration: No
International Travel: Yes, Portugal - 0 years, 0 months, 7 days

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 Tennessee, by adopting many perspectives of the research results for undergraduate students' course projects and senior design topics. The project has supported one PhD student working on his 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 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.

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.