Montage: An Integrated End-to-End Design and Development Framework for Wireless Networks

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Introduction

This project titled "Montage: An Integrated End-to-End Design and Development Framework for Wireless Networks" is developing the first academic end-to-end multi-layer simulator and emulator for wireless networks. Montage —an integrated protocol development environment —will support the evolutionary design, development, and test of wireless network protocols for a wide range of network topologies, usage patterns, applications, and physical environments. Montage will enable wireless and ad-hoc mobile network researchers and system operators across the country to design, develop, and analyze wireless hardware, network protocols, middleware algorithms, and network applications in a single integrated public-domain environment. The project was launched in September 2003 with a team comprised of five faculty members and seven students from The University of Texas at Austin and Virginia Polytechnic Institute and State University. The project has a three year duration, ending August 2006.

Participants

Faculty

- Prof. Theodore S. Rappaport, The University of Texas at Austin, Dept. of Electrical and Computer Engineering
- Prof. James C. Browne, The University of Texas at Austin, Dept. of Computer Science
- Prof. Naren Ramakrishnan, Virginia Polytechnic Institute and State University, Dept. of Computer Science
- Prof. Sanjay Shakkottai, The University of Texas at Austin, Dept. of Electrical and Computer Engineering
- Prof. Srinidhi Varadarajan, Virginia Polytechnic Institute and State University, Dept. of Computer Science

Students

The Montage project involves 9 students, including 3 Ph.D. students, 4 M.S. students, and 2 undergraduate students. Student participants include:

Ph. D.

- Chen Na, The University of Texas at Austin, Dept. of Electrical and Computer Engineering
- Huihui Wang, The University of Texas at Austin, Dept. of Electrical and Computer Engineering
- Yung Yi, The University of Texas at Austin, Dept. of Electrical and Computer Engineering

Masters

- Craig Bergstrom, Virginia Polytechnic Institute and State University, Dept. of Computer Science
- Jeremy Chen, The University of Texas at Austin, Dept. of Electrical and Computer Engineering
- Sundar Subramanian, The University of Texas at Austin, Dept. of Electrical and Computer Engineering
- Madhulika Yalamanchi, The University of Texas at Austin, Dept. of Electrical and Computer Engineering

Undergraduate

- Kevin Albert, The University of Texas at Austin, Dept. of Electrical and Computer Engineering
- Matthew Zappitello, The University of Texas at Austin, Dept. of Electrical and Computer Engineering

Activities and Findings

When there is full attendance by faculty and students, there is excellent interchange and sharing of ideas and viewpoints which lead to a broad experience. Students have been presenting lectures of their work, and it has fostered a good culture of sharing of ideas. During the first year, there was considerable work accomplished, although the team is still gelling.

The Montage project has demonstrated the need to carefully think through the impact of time and spatial events in a large scale simulator, and has required the PI's and the students to determine suitable methods for simulating timing events that can be parallelized, and abstracted to arbitrary granularity. For example, the Poems simulation methodology of University of Texas needs to be unified with the Weaves Methodology of Virginia Tech, and students and faculty have developed a framework to allow both simulation approaches to work harmoniously. At the same time, the physical layer and network layer discrete time simulation capabilities of S4W, and the end-to-end

abstractions of network flows, must work with the combined Poems and Weaves simulation fabric, and this has required the team to begin exploring hooks from the higher level abstractions to the parallel simulation kernel. Work in these areas is progressing.

The S4W simulation environment is now in use by several other universities, including the University of Toronto, and University of Texas students are evaluating S4W for usability and improvement, and providing feedback to Virginia Tech students and faculty. This multi-university interaction is key for evolving Montage into a powerful public domain tool for research.

Several recent breakthroughs in this research program include:

a. A new, fast way of modeling the effects of diffraction in radio propagation simulation. Diffraction is how RF energy propagates in non-line-of-sight situations, and the fast methodology may be implemented in S4W to provide substantially more accurate signal strength modeling
b. New analytical bounds have been developed that show the size and delay of various network topologies, particular in ad-hoc networks, and these results will be useful to benchmark and enhance the Montage simulator.
c. A fluid modeling approach has been validated and implemented in hardware, leading to FluNET, a computer-implemented end-to-end simulator for wired networks. This will be extended to wireless network simulations.
d. A new approach, Time Dilation, for simulating events that have widely varying time scales, has been discovered and is being investigated for implementation in Montage.
e. We have successfully mapped physical layer models, such as propagation and interference, into end-user application layer performance models, thereby allowing site-specific propagation modeling to accurately predict wireless device performance.

In addition, several students on the Montage project have successfully completed their degree or reached important milestones in their academic career. These include:

Jeremy Chen, Sundar Subramanian, and Madhulika Yalamanchi received their MS degrees in May 2004, and Jeremy and Sundar are staying involved in this program as Ph.D. students. Yung Yi proposed his Ph.D. proposal and it was approved in May 2004.

A snapshot of activities by individual faculty on the Montage project is provided below:

The University of Texas at Austin

Prof. James C. Browne
Integration of the POEMS capabilities for compositional development of hybrid distributed programs which combine performance model components with realized code components with the Weaves capability for simulation of execution environments has been initiated.

A capability for adapting hybrid distributed programs by dynamically linking either model or realized code at runtime has been developed. This capability enables runtime adaptation of hybrid distributed programs to evolving execution environments.

Continued development of the P-COM^2 compilation system including integration of the dynamic linking feature described above.

Prof. Theodore S. Rappaport
Ted Rappaport has been working with his own students, as well as faculty at Virginia Tech to further the S4W capabilities. S4W will eventually become a key part of the Montage simulator under joint development by the University of Texas (UT) and Virginia Tech (VT).

Working with Prof. Naren Ramakrishnan at Virginia Tech, Rappaport and his Ph.D. student Huihui Wang have successfully implemented S4W at the University of Texas, and are looking to use the UT cluster, or a smaller cluster internal to WNCG, to run improved versions of S4W. Ms Wang is currently evaluating the latest version of S4W from VA Tech, and is providing user feedback and suggestions, as well as encouraging other universities and students to use the simulation environment. In addition, Ms. Wang has developed a curve-fitting approach to rapid diffraction modeling, a technique that is ideally suited to the S4W environment. Ms. Wang will eventually implement her new diffraction curve fitting approach in S4W.

Rappaport's student Jeremy Chen successfully completed and published his Masters Thesis in May 2004, on the topic of blind throughput prediction for wireless networks using various end-user applications. This work will allow further abstraction in S4W/Montage. Chen has demonstrated that measurement-based or prediction-based models for throughput can be accurately rendered from site-specific propagation software tools. This holds promise for autonomous network control as well as rapid deployment for application-specific Wireless LANs. Mr. Chen plans to continue on the Montage project for his PhD beginning in the Fall of 2004. He is currently working in industry for the summer.

Rappaport's Ph.D. student Chen Na has explored real-world behavior of Wireless LAN network traffic in several restaurants, and has served as mentor for Jeremy Chen. Mr. Chen also successfully built a real-time monitoring software kernel for use in the ECE wireless network, so that real time traffic statistics may be recorded within the ECE building at UT. This will provide means for further measurements and modeling of real time Wireless LAN traffic behavior and will allow Chen to begin exploration of real time network control algorithms on an application-sensitive basis. This work will also allow model abstractions for use in simulation of S4W/Montage

Two star honors undergraduates, Kevin Albert and Matthew Zappitello, began exploring position-location methodologies within and around buildings, and will be funded on a

NSF Research Experience grant to work on the Montage project beginning Fall of 2005. They currently are working in industry for the summer.

Prof. Sanjay Shakkottai

FluNet: Fluid models have been popular for network analysis and design. Over the past decade, such models have been used extensively in the modeling and analysis of the Internet. Much of this work has focused on the design of end host controllers and control algorithms at routers (the marking functions) for stable end-to-end operation over the Internet. In our research, we have developed a hybrid simulator, FluNet, which uses a mixture of packet and fluid models for fast network simulation. The technical innovations in our work include low-complexity models for queues, as well as combining fluid and packet models in a real time environment [3,6].

Network Algorithms: We have explored a variety of network algorithms for wireless and sensor networks. These include algorithms for congestion control over a community roof-top network [1], as well as understanding searching, querying [2] and power control over a sensor network [4,5,7].

A prototype of FluNet, a fluid network simulator (funded in part by the Montage project) was on display during the WNCG open house. Visitors included state congressmen, Austin business leaders, academic visitors from Texas universities, and students.

Virginia Polytechnic Institute and State University

Naren Ramakrishnan, with Virginia Tech Masters student Craig Bergstrom, has begun integrating the S4W problem solving environment (funded from NSF NGS grant EIA-9974956) into the simulation model library that will form the core of the Montage system. In particular, the propagation prediction functionality of S4W (utilizing a high-performance parallel ray tracing engine) has been packaged and made available to the UT Austin subgroup for use in characterizing various indoor and combined indoor-outdoor environments. Eventually, all models supported by S4W (deterministic, stochastic, as well as surrogate approximations) will be available for use in realizing Montage simulations. Important issues in this integration and porting exercise were unbundling dependencies between S4W components, improving the automatic configuration of the ray tracer, and providing database access and experiment management support to all aspects of ray tracing runs.

Meanwhile, together with Srinidhi Varadarajan, Naren Ramakrishnan has completed a preliminary integration of S4W with the ONE (Open Network Emulator). This integration achieves a complete end-to-end simulation of a file transfer protocol over a WCDMA link realized using S4W's models, allowing us to study the performance of the modeled system in a realistic mobile setting. The realized simulation serves the basis for more complex scenarios that will be supported by Montage, such as optimization for end-to-end design goals, combining simulation, emulation, and direct-code execution, and rapid study of dynamic, ad-hoc, wireless networks.

Finally, Naren Ramakrishnan is working with Prof. Rappaport's student Jeremy Chen, utilizing his measurement data gathered at commercial Austin outlets to improve the modeling capabilities of Montage. This work is expected to result in better surrogate approximations that can be embedded in costly computational loops, such as global optimization or data mining.

Publications and Products

Papers Published

1. Y. Yi and S. Shakkottai, "Hop-by-hop Congestion Control over a Wireless Multi-hop Network," *Proceedings of IEEE Infocom*, Hong Kong, March 2004.

2. S. Shakkottai, "Asymptotics of Query Strategies over a Sensor Network," *Proceedings of IEEE Infocom*, Hong Kong, March, 2004.

3. Y. Yi, S. Deb, and S. Shakkottai, "Short Queue Behavior and Rate Based Marking," *Proceedings of the 38th Annual Conference on Information Sciences and Systems (CISS)*, Princeton, NJ, March 2004.

4. W. Wu, A. Arapostathis, and S. Shakkottai, "Optimal Power Allocation for a Wireless Channel under Heavy Traffic Approximation," *Proceedings of the 38th Annual Conference on Information Sciences and Systems (CISS)*, Princeton, NJ, March 2004.

5. M. Airy, B. Mondal, R. Heath, and S. Shakkottai, "Iterative, Rate-Constrained Capacity of MIMO Broadcast Channels," *Proceedings of the 38th Annual Conference on Information Sciences and Systems (CISS)*, Princeton, NJ, March 2004.

6. Y. Yi, S. Deb, and S. Shakkottai, "Time-scale Decomposition and Equivalent Rate Based Marking," *IMA Worshop: Measurement, Modeling and Analysis of the Internet*, University of Minesota, MN, January 2004.

7. B. Rengarajan, J. K. Chen, S. Shakkottai, T. S. Rappaport, "Connectivity of Sensor Networks with Power Control", *IEEE Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, November 9-12, 2003.

8. S. Shakkottai, T. S. Rappaport, P. C. Karlsson, "Cross-Layer Design for Wireless Networks", *IEEE Communications Magazine*, Volume 41, No. 10, October 2003, pp. 74-80.

Papers to Appear

1. R. Skidmore, A. Verstak, N. Ramakrishnan, T.S. Rappaport, L.T. Watson, J. He, S. Varadarajan, C.A. Shaffer, J. Chen, K.K. Bae, J. Jiang, and W.H. Tranter, "Towards Integrated PSEs for Wireless Communications: Experiences with the S4W and

SitePlanner Projects", ACM SIGMOBILE Mobile Computing and Communications Review (MC^2R), 2004, to appear.

2. S. Varadarajan and N. Ramakrishnan, Novel Runtime Systems Support for Adaptive Compositional Modeling in PSEs, Future Generation Computer Systems (Special Issue on `Complex PSEs for Grid Computing'), 2004, to appear.

3. H. Wang and T. S. Rappaport, "A Parametric Formulation of the UTD Diffraction Coefficients for a Dielectric Wedge", *IEEE AP-S International Symposium on Antennas and Propagation*, Accepted on May 5, 2004

Papers Submitted

1. N. Mahmood, G. Deng and J.C. Browne, "Evolutionary Performance-Oriented Development of Parallel Programs by Composition of Components," *LCPC 17*, Submitted.

2. Y. Yi and S. Shakkottai, "Hop-by-hop Congestion Control over a Wireless Multi-hop Network," *IEEE/ACM Transactions on Networking*, Submitted

3. C. Na, J. K. Chen, T. S. Rappaport, "Measured Traffic Statistics and Throughput of IEEE 802.11b Public WLAN Hotspots with Three Different Applications", *IEEE Transactions on Wireless Communications*, Submitted on February 27, 2004.

4. C. Na, J. K. Chen, T. S. Rappaport, "Hotspot Traffic Statistics and Throughput Models for Several Applications", *IEEE Globecom 2004,* Submitted on February 27, 2004.

Papers in Preparation

1. Madhulika Yalamanchi, N. Mahmood and J.C. Browne, "Dynamic Linking for Performance Adaptation of Component-Based Programs"

2. Kevin Kane and J.C. Browne, "Broadcast Based Distributed Programming"

Websites

http://www.ece.utexas.edu/~wireless/montage.html

Research Products

1. Developed a hybrid simulator, FluNet, which uses a mixture of packet and fluid models for fast network simulation.
2. Continued development of the P-COM2 compilation system
3. Built a real-time monitoring software kernel for use in the ECE wireless network, so that real time traffic statistics may be recorded within the ECE building at UT, using the installed wireless LAN infrastructure.

4. Completed a preliminary integration of S4W with the ONE (Open Network Emulator).

Contributions

The Montage Project has brought together a group of faculty with a wide range of lexicons, experiences, and viewpoints from both the engineering and computer science world of two major public universities. The software and findings are being disseminate widely, to the academic and industrial communities, and promise to impact the wireless communications field to a very large extent.

In the area of network simulation for wireless communications, we have achieved some important breakthroughs in fast-simulation and modeling approaches along with analytical bounds on large-network behavior. These results not only help with developing the MONTAGE simulation modeling, but offer insights into the behavior of large networks. In particular, this work will allow wireless carriers to accurately simulate the impact of large-scale wireless networks having hundreds to millions of users. This work provides a framework for predicting performance, capacity, and potential useful applications of sensor-based and ad-hoc networks, containing millions of devices. Position location is also an area being explored by this program, and while no results are available yet, the framework for simulating, predicting, and managing networks with position-aware capabilities will be an outcome of this work and will have important relevance in future networks.

The Montage Project has demonstrated the need to carefully think through the impact of time and spatial events in a large scale simulator, and has required the PI's and the students to determine suitable methods for simulating timing events that can be parallelized, and abstracted to arbitrary granularity. For example, the Poems simulation methodology of University of Texas is being unified with the Weaves Methodology of Virginia Tech, and students and faculty have developed a framework to allow both simulation approaches to work harmoniously. This promises to provide a unified framework for simulation that will be usable by a large number of institutions doing work on large-scale network problems.

At the same time, the physical and network layer discrete time simulation capabilities of S4W, and the end-to-end abstractions of network flows, are being built on the combined Poems and Weaves simulation fabric, and this has required the team to begin exploring hooks from the higher level abstractions to the parallel simulation kernel. Work in these areas is progressing.

The S4W simulation environment is now in use by several other universities, including the University of Toronto, and University of Texas students are evaluating S4W for usability and improvement, and providing feedback to Virginia Tech students and faculty. This multi-university interaction is key for evolving Montage into a powerful public domain tool for research throughout the academic community.