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Cyber Cattle on the Wireless Range

Computer-controlled herding of cattle is the novel area of research being explored by CMC faculty member Daniela Rus and her group of cyber cowboys. Using an eTrex GPS, Zaurus PDA, small guitar amplifiers, and multihop wireless networking, the team has designed a cow collar which uses sounds to create virtual fences to guide cattle for roundup and to modify their grazing behavior. The team includes Dr. Peter Corke from CSIRO in Australia, Dr. Zack Butler from the Rochester Institute of Technology, and Ron Peterson, staff engineer in the Dartmouth CS Department. They have also recently started working together with Dr. Dean Anderson, Research Animal Scientist from USDA's Jornada Experimental Range and Craig Hale of Future Segue who hold key patents on virtual fence technology. This research is definitely off the beaten path for the CMC team, notes Ron Peterson. "I never imagined that working on research in computer science would one day have me chasing cows across a Vermont pasture, trying to coax them to stand still so I could reconnect their computers."

Daniela describes how a group of robot scientists happened to become involved in this unusual area of robotics research: "In March 2003, I was in Australia to meet with Peter Corke on a different project. While there, I visited a friend and former student who works in the cattle industry and we talked about some of his key challenges. His company deals with hundreds of thousands of animals. Peter Corke (from CSIRO) and I went to visit one of his cow stations in the Northern Territory (near Darwin). (This is how ranches are called in Australia). After spending two days looking around and talking to the people who manage the daily cow operations, we returned very inspired to do the work. Then during the summer of 2003 we connected with Cobb Hill Farms in Vermont and tried our first smart collar prototypes there. In the meantime, we started doing a literature survey and discovered people like USDA's Dr. Dean Anderson who has been thinking about virtual fences for over 30 years. We contacted Dean, visited his team, and decided that bringing our computation expertise together with their biological expertise would lead to bigger and greater progress and we are currently working on some experiments that bring our work together."

CMC professor Daniela Rus, field-testing the GPS-enabled, PDA-based collar they designed for a cow in vermont.

Real barbed wire and electric fences on the open range can cost cattle ranchers huge sums to build and maintain, hence the cost savings of replacing some fences with virtual fences can be significant. Other uses of virtual fences include roundup and foraging management to get the best use from the land. Roundup of cattle is done once or twice a year for health checks, branding, immunizations, and sales, and is currently accomplished using helicopters, trucks, and motorcycles. The cost of a helicopter and pilot for roundup is around $500/hour. Truck and motorcycle roundups involve a team of cow handlers with similar costs, so virtual herding has the potential to minimize these costs, while also freeing up ranch hands for other tasks. Foraging management would allow ranchers to both get their cattle to the best feed and to make the best use of all the forage on the land, resulting in fatter cattle and being able to raise more cattle per acre. Monitoring the cattle can also result in more humane treatment of them. The virtual fence software uses techniques from robot motion planning algorithms to plan optimal routes for the cattle being herded. Multihop wireless technology keeps the rancher in contact with the herd and allows monitoring the cows' locations as well as sending herding commands. While using sound alone has not so far proven effective, the combination of the CMC team's algorithms with the USDA team's sound+shock collars (which have proven very effective in creating virtual fences) looks like a win. Rus explains, "Apparently, biologists like Dean Anderson had been thinking about virtual fences for some time. We only found out about this when we started researching the literature. So our real contribution has been to bring this problem to the computer science and robotics community from the biology community." Says Rus, "This interdisciplinary approach will combine expertise from both fields, leading to bigger and greater progress."

CMC News

Dartmouth wins EDUCAUSE Award

EDUCAUSE recently gave its 2004 Award for Excellence in Networking: Innovation in Network Technology, Services, and Management. The award acknowledged Dartmouth's efforts to create a 100 percent, campus-wide wireless computing network environment that supports teaching, learning, research, and daily life on the campus. The wireless network has helped launch new activities, from classroom and teaching enhancements to research initiatives to corporate partnerships. More information about EDUCAUSE and the award can be found at www.educause.edu.

Intel and Sun support CMC research

Intel's University Research Program recently awarded a grant to Sean Smith and his PKI/Trust team to explore "Scalable Authorization for Communities of Mobile Devices," in which they will explore how to use various forms of public-key assertions to enable humans to create, in their ad hoc communities of devices, trust relationships that match those between the users.

Sun's Internet Security Research Group recently awarded a grant to Sean Smith and his PKI/Trust team to explore using the tools of distributed simulation to evaluate the scalability and performance of experimental path discovery and revocation protocols, and also to continue Dartmouth's PKI rollout.

Cybenko Named Outstanding Mentor

Dartmouth's Graduate Student Council recently presented Prof. George Cybenko with the Arts and Sciences Graduate Faculty Mentor Award for his deep commitment to fostering the professional and personal development of graduate students. One student said, "meeting with him is always enlightening. He always has ideas and suggestions to share. He is scientifically and personally generous with students. His guidance is the principal reason why his research group (which is composed of more than ten people between students and researchers) is compact and productive."

Minkyong Kim joins CMC

A recent Ph.D. from Brian Noble's group at the University of Michigan, postdoctoral research associate Minkyong Kim joined David Kotz's group in October. At Michigan she developed the Fluid Replication system, a wide-area distributed file system for mobile users that provides safety and visibility to file updates for wide-area with performance comparable to the local area.

McKinsey Teams with CMC on a Mobile Computing and Communications Study

When, where, and why do Dartmouth students use the wireless network? How does it change their behavior? Last summer (2004), Denise Anthony, Tristan Henderson, and David Kotz conducted an extensive study of wireless usage by Dartmouth undergraduates. Twenty-nine undergraduates carried pagers for seven days and were randomly paged up to 8 times per day. At each page, students reported where they were; what, if any, devices and networks they were using; and communication in the previous 30 minutes.

The ubiquitous wireless network on the Dartmouth campus enables students to be both mobile and connected throughout their day. On average, students were using the wireless network for 6 hours per day, and 40% of the sample used wireless for more than 6 hours per day.

Two-thirds of the students were "mobile" on one or more days of the study, where mobility is defined as accessing two or more wireless Access Points (APs) at least 50 meters apart. Mobile users visited an average of 23 different APs during the week. Not surprisingly, wireless usage and mobility are strongly correlated. Mobile users were on the wireless network an average of 7.7 hours per day, compared to non-mobile users who were on the wireless network an average of 3.3 hours per day.

The ubiquitous wireless network allows students to go online almost anywhere. Much of the time they spend in the library (65%) is spent online, and 10% of the time they are in classes they are online. More surprising are the findings that students go online in social spaces as well as study spaces. For example, about one quarter of the time they are at a friends' place they are online, and about one third of the time they are in a dining hall or off campus they are online. As one student said, "[Wireless] lets me move my study space to wherever I want it to be."

Most of the time online, students are engaged in communication. As anyone familiar with Dartmouth's "Blitzmail culture" knows the primary mode of communication for students is email (87% of all communication). Students also use instant messaging (IM) technology (19%) and to a much lesser extent, phones, including standard telephone (7%), cell phones (2%) and Voice-over IP phones (2%). The percentages of communication by each mode add to more than 100% because students often used multiple modes of communication at the same time. For example, 26% of the time they were communicating via email, they were also using IM.

Students say that the wireless network helps them to maintain and even strengthen their social relationships. One student said, "I think I communicate with people more often because I have wireless, just because I can check (email) anywhere." Another said, "I think relationships are stronger because I am more easily able to communicate with people. I mean, I have my laptop on me pretty much all the time so its really easy for me to check [email], or respond to an instant message. So if I always have access to it, its helped to develop and strengthen relationships."

This study was generously funded by McKinsey and Company. We also received significant help from Peter Glenshaw, Director of Corporate & Venture Initiatives, and research assistance from Linda Lomelino '06.

New Research Papers

Complete Text at http://cmc.cs.dartmouth.edu/papers

Javed Aslam, Zack Butler, Florin Constantin, Valentino Crespi, George Cybenko, and Daniela Rus. Tracking a moving object with a binary sensor network. In Proceedings of the First International Conference on Embedded Networked Sensor Systems (SenSys), November 2003.

In this paper we examine the role of very simple and noisy sensors for the tracking problem. We propose a binary sensor model, where each sensor's value is converted reliably to one bit of information only: whether the object is moving toward the sensor or away from the sensor. We show that a network of binary sensors has geometric properties that can be used to develop a solution for tracking with binary sensors and present resulting algorithms and simulation experiments. We develop a particle filtering style algorithm for target tracking using such minimalist sensors. We present an analysis of fundamental tracking limitation under this sensor model, and show how this limitation can be overcome through the use of a single bit of proximity information at each sensor node. Our extensive simulations show low error that decreases with sensor density.

Z. Butler, P. Corke, R. Peterson, and D. Rus. Dynamic virtual fences for controlling cows. In Proceedings of the Ninth International Symposium on Experimental Robotics. June 2004.

A virtual fence is created by applying an aversive stimulus to an animal when it approaches a predefined boundary. It is implemented by a small animalborne computer system with a GPS receiver. This approach allows the implementation of virtual paddocks inside a normal physically fenced paddock. Since the fence lines are virtual they can be moved by programming to meet the needs of animal or land management. This approach enables us to consider animals as agents with natural mobility that are controllable and to apply a vast body of theory in motion planning. In this paper we describe a herdanimal simulator and physical experiments conducted on a small herd of 10 animals using a Smart Collar. The Smart Collar consists of a GPS, PDA, wireless networking and a sound amplifier. In particular we describe a motion planning algorithm that can move a virtual paddock which is suitable for mustering cows. We present simulation results and data from experiments with 8 cows equipped with Smart Collars.

Zack Butler, Peter Corke, Ronald Peterson, and Daniela Rus. Virtual fences for controlling cows. In Proceedings of the IEEE 2004 International Conference on Robotics and Automation, Volume 4. May 2004.

We describe a moving virtual fence algorithm for herding cows. Each animal in the herd is given a smart collar consisting of a GPS, PDA, wireless networking and a sound amplifier. Using the GPS, the animal's location can be verified relative to the fence boundary. When approaching the perimeter, the animal is presented with a sound stimulus whose effect is to move away. We have developed the virtual fence control algorithm for moving a herd. We present simulation results and data from experiments with 8 cows equipped with smart collars.

Zack Butler, Peter Corke, Ronald Peterson, and Daniela Rus. Virtual fences for controlling cows. In Proceedings of the Workshop on Applications of Mobile Embedded Systems (WAMES at MobiSys 2004), June 2004.

Our goal is to develop computational approaches for studying groups of agents with natural mobility and social interactions. Such systems differ in many ways from engineered mobile systems because their agents can move on their own due to complex natural behaviors as well as under the control of the environment (for example drifting to follow wind patterns). We wish to model such systems using physical data and to use the models for controlling the movement of the mobile agents and the information propagation between them using virtual fences, implemented on smart networked collars attached to the animals. Our main motivation and application is in the agricultural domain. Herds of animals such as cattle are complex systems. There are interesting interactions between individuals, such as friendship, kinship, group formation, leading and following. There are complex interactions with the environment, such as looking for a water source in a new paddock by perimeter tracing along the fence and random walking within the perimeter. Such behaviors are well known to farmers but not so well documented. Furthermore, limited control can be exerted whose effect is to move the animals around. This could be greatly beneficial in terms of reducing the amount of expensive fence maintenance and mustering required by ranchers.

Guanling Chen and David Kotz. Dependency management in distributed settings (poster abstract). In International Conference on Autonomic Computing (ICAC-04), May 2004.

Ubiquitous-computing environments are heterogeneous and volatile in nature. Systems that support ubicomp applications must be self-managed, to reduce human intervention. In this paper, we present a general service that helps distributed software components to manage their dependencies. Our service proactively monitors the liveness of components and recovers them according to supplied policies. Our service also tracks the state of components, on behalf of their dependents, and may automatically select components for the dependent to use based on evaluations of customized functions. We believe that our approach is flexible and abstracts away many of the complexities encountered in ubicomp environments. In particular, we show how we applied the service to manage dependencies of context-fusion operators and present some experimental results.

Guanling Chen, Ming Li, and David Kotz. Design and implementation of a large-scale context fusion network. In First Annual International Conference on Mobile and Ubiquitous Systems: Networking and Services (Mobiquitous), August 2004.

In this paper we motivate a Context Fusion Network (CFN), an infrastructure model that allows context-aware applications to select distributed data sources and compose them with customized data-fusion operators into a directed acyclic information fusion graph. Such a graph represents how an application computes high-level understandings of its execution context from low-level sensory data. Multiple graphs by different applications inter-connect with each other to form a global graph. A key advantage of a CFN is re-usability, both at code-level and instance-level, facilitated by operator composition. We designed and implemented a distributed CFN system, Solar, which maps the logical operator graph representation onto a set of overlay hosts. In particular, Solar meets the challenges inherent to heterogeneous and volatile ubicomp environments. By abstracting most complexities into the infrastructure, we believe Solar facilitates both the development and deployment of context-aware applications. We present the operator composition model, basic services of the Solar overlay network, and programming support for the developers. We also discuss some applications built with Solar and the lessons we learned from our experience.

Guanling Chen and David Kotz. A Case Study of Four Location Traces. Technical Report TR2004-490, Dept. of Computer Science, Dartmouth College, February 2004.

Location is one of the most important context information that an ubiquitous-computing application may leverage. Thus understanding the location systems and how location-aware applications interact with them is critical for design and deployment of both the location systems and location-aware applications. In this paper, we analyze a set of traces collected from two small-scale one-building location system and two large-scale campus-wide location systems. Our goal is to study characteristics of these location systems ant how these factors should be taken into account by a potentially large number of location-aware applications with different needs. We make empirical measurements of several important metrics and compare the results across these location systems. We discuss the implication of these results on location-aware applications and their supporting software infrastructure, and how location systems could be improved to better serve applications' needs. In places where possible, we use location-aware applications discussed in existing literatures as illustrating examples.

New Research Papers (Continued)

Peter Corke, Ronald Peterson, and Daniela Rus. Coordinating aerial robots and sensor networks for localization and navigation. In Proceedings of the Seventh International Symposium on Distributed Autonomous Robotic Systems, Distributed Autonomous Robotic Systems 6. June 2004.

We consider multi-robot systems that include sensor nodes and aerial or ground robots networked together. We describe two cooperative algorithms that allow robots and sensors to enhance each other's performance. In the first algorithm, an aerial robot assists the localization of the sensors. In the second algorithm, a localized sensor network controls the navigation of an aerial robot. We present physical experiments with an flying robot and a large Mica Mote sensor network.

Peter Corke, Steven Hrabar, Ronald Peterson, Daniela Rus, Srikanth Saripalli, and Gaurav Sukhatme. Autonomous deployment and repair of a sensor network using an unmanned aerial vehicle. In Proceedings of the IEEE 2004 International Conference on Robotics and Automation, May 2004.

We describe a sensor network deployment method using autonomous flying robots. Such networks are suitable for tasks such as large-scale environmental monitoring, or for command and control in emergency situations. We describe in detail the algorithms used for deployment and for measuring network connectivity and provide experimental data we collected from field trials. A particular focus is on determining gaps in connectivity of the deployed network and generating a plan for a second, repair, pass to complete the connectivity. This project is the result of a collaboration between three robotics labs (CSIRO, USC, and Dartmouth).

Peter Corke, Ron Peterson, and Daniela Rus. Communication-assisted localization and navigation for networked robots. International Journal of Robotics Research, June 2004. Accepted for publication.

This paper introduces the application of a sensor network to navigate a flying robot. We have developed distributed algorithms and efficient geographic routing techniques to incrementally guide one or more robots to points of interest based on sensor gradient fields, or along paths defined in terms of Cartesian coordinates. These include a distributed robot-assisted localization algorithm, a distributed communication-assisted path computation algorithm for the robot and a distributed communication-assisted navigation algorithm to guide the robot. The robot itself is an integral part of the localization process which establishes the positions of sensors which are not known a priori. The sensor network is an integral part of the computation and storage of the robot's path. We use this system in a large-scale outdoor experiment with Mote sensors to guide an autonomous helicopter along a path encoded in the network. We also describe how a human can be guided using a simple handheld device that interfaces to this same environmental infrastructure.

P. Corke, S. Hrabar, R. Peterson, D. Rus, S. Saripalli, and G. Sukhatme. Deployment and connectivity repair of a sensor net with a flying robot. In Proceedings of the Ninth International Symposium on Experimental Robotics. June 2004.

We consider multi-robot systems that include sensor nodes and aerial or ground robots networked together. Such networks are suitable for tasks such as large-scale environmental monitoring or for command and control in emergency situations. We present a sensor network deployment method using autonomous aerial vehicles and describe in detail the algorithms used for deployment and for measuring network connectivity and provide experimental data collected from field trials. A particular focus is on determining gaps in connectivity of the deployed network and generating a plan for repair, to complete the connectivity. This project is the result of a collaboration between three robotics labs (CSIRO, USC, and Dartmouth.)

Valentino Crespi and George Cybenko. Decentralized algorithms for sensor registration. In Proceedings of the International Joint Conference on Neural Networks (IJCNN), Portland, OR, July 2003.

In this paper we investigate a problem arising in decentralized registration of sensors. The application we consider involves a heterogeneous collection of sensors- some sensors have on-board Global Positioning System (GPS) capabilities while others do not. All sensors have wireless communications capability but the wirele ss communication has limited effective range. Sensors can communicate only with other sensors that are within a fixed distance of each other. Sensors with GPS capability are self-registering. Sensors without GPS capability are less expensive and smaller but they must compute estimates of their location using estimates of the distances between themselves and other sensors within their radio range. GPS-less sensors may be several radio hops away from GPS-capable sensors so registration must be inferred transitively. Our approach to solving this registration problem involves minimizing a global potential or penalty function by using only local information, determined by the radio range, available to each sensor. The algorithm we derive is a special case of a more general methodology we have developed called "Emergence Engineering".

Nikita E. Dubrovsky. Mobile agents simulation with DaSSF. Technical Report TR2004-499, Dept. of Computer Science, Dartmouth College, June 2004.

Mobile agents are programs that can migrate from machine to machine in a network of computers and have complete control over their movement. Since the performance space of mobile agents has not been characterized fully, assessing the effectiveness of using mobile agents over a traditional client/server approach currently requires implementing an agent system and running time-consuming experiments.

This report presents a simple mobile-agent simulation that can provide quick information on the performance and scalability of a generic information retrieval (IR) mobile-agent system under different network configurations. The simulation is built using the DaSSF and DaSSFNet frameworks, resulting in high performance and great configuration flexibility. This report also implements a real D'Agents mobile-agent IR system, measuring the performance of the system. A comparison of these real-world performance results and those given by the simulation suggest that the simulation has good accuracy in predicting the scalability of a mobile-agent system. Thus this report argues that simulation provides a good way to quickly assess the performance and scalability of an IR mobile-agent system under different network configurations.

Nicholas C. Goffee, Sung Hoon Kim, Sean Smith, Punch Taylor, Meiyuan Zhao, and John Marchesini. Greenpass: Decentralized, PKI-based authorization for wireless LANs. In Proceedings of the Third Annual PKI R&D Workshop, NIST, September 2004.

In Dartmouth's ``Greenpass'' project, we're building an experimental system to explore two levels of authorization issues in the emerging information infrastructure. On a practical level, we want to enable only authorized users to access an internal wireless network-while also permitting appropriate users to delegate internal access to external guests, and doing this all with standard client software. On a deeper level, PKI needs to be part of this emerging information infrastructure-since sharing secrets is not workable. However, the traditional approach to PKI-with a centralized hierarchy based on global names and heavy-weight X.509 certificates-has often proved cumbersome. On this level, we want to explore alternative PKI structures that might overcome these barriers.

By using SPKI/SDSI delegation on top of X.509 certificates within EAP-TLS authentication, we provide a flexible, decentralized solution to guest access that reflects real-world authorization flow, without requiring guests to download nonstandard client software. Within the ``living laboratory'' of Dartmouth's wireless network, this project lets us solve real problem with wireless networking, while also experimenting with trust flows and testing the limits of current tools.

New Research Papers (Continued)

Nicholas C. Goffee. **Greenpass client tools for delegated authorization in wireless networks.** Master's thesis, Dept. of Computer Science, Dartmouth College, June 2004. Available as Dartmouth Computer Science Technical Report TR2004-509.

Dartmouth's Greenpass project seeks to provide strong access control to a wireless network while simultaneously providing flexible guest access; to do so, it augments the Wi-Fi Alliance's existing WPA standard, which offers sufficiently strong user authentication and access control, with authorization based on SPKI certificates. SPKI allows certain local users to delegate network access to guests by issuing certificates that state, in essence, ``he should get access because I said it's okay.'' The Greenpass RADIUS server described in Kim's thesis [55] performs an authorization check based on such statements so that guests can obtain network access without requiring a busy network administrator to set up new accounts in a centralized database. To our knowledge, Greenpass is the first working delegation-based solution to Wi-Fi access control.

My thesis describes the Greenpass client tools, which allow a guest to introduce himself to a delegator and allow the delegator to issue a new SPKI certificate to the guest. The guest does not need custom client software to introduce himself or to connect to the Wi-Fi network. The guest and delegator communicate using a set of Web applications. The guest obtains a temporary key pair and X.509 certificate if needed, then sends his public key value to a Web server we provide. The delegator looks up her guest's public key and runs a Java applet that lets her verify her guests' identity using visual hashing and issue a new SPKI certificate to him. The guest's new certificate chain is stored as an HTTP cookie to enable him to `push' it to an authorization server at a later time. I also describe how Greenpass can be extended to control access to a virtual private network (VPN) and suggest several interesting future research and development directions that could build on this work.

Robert S. Gray, David Kotz, Calvin Newport, Nikita Dubrovsky, Aaron Fiske, Jason Liu, Christopher Masone, Susan McGrath, and Yougu Yuan. **Outdoor experimental comparison of four ad hoc routing algorithms.** In Proceedings of the ACM/IEEE International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), October 2004.

Most comparisons of wireless ad hoc routing algorithms involve simulated or indoor trial runs, or outdoor runs with only a small number of nodes, potentially leading to an incorrect picture of algorithm performance. In this paper, we report on an outdoor comparison of four different routing algorithms, APRL, AODV, ODMRP, and STARA, running on top of thirty-three 802.11-enabled laptops moving randomly through an athletic field. This comparison provides insight into the behavior of ad hoc routing algorithms at larger real-world scales than have been considered so far. In addition, we compare the outdoor results with both indoor (``tabletop'') and simulation results for the same algorithms, examining the differences between the indoor results and the outdoor reality. Finally, we describe the software infrastructure that allowed us to implement the ad hoc routing algorithms in a comparable way, and use the same codebase for indoor, outdoor, and simulated trial runs.

Tristan Henderson, David Kotz, and Ilya Abyzov. **The changing usage of a mature campus-wide wireless network.** In Proceedings of the Tenth Annual International Conference on Mobile Computing and Networking, September 2004.

Wireless Local Area Networks (WLANs) are now commonplace on many academic and corporate campuses. As ``Wi-Fi'' technology becomes ubiquitous, it is increasingly important to understand trends in the usage of these networks.

This paper analyzes an extensive network trace from a mature 802.11 WLAN, including more than 550 access points and 7000 users over seventeen weeks. We employ several measurement techniques, including syslogs, telephone records, SNMP polling and tcpdump packet sniffing. This is the largest WLAN study to date, and the first to look at a large, mature WLAN and consider geographic mobility. We compare this trace to a trace taken after the network's initial deployment two years ago.

We found that the applications used on the WLAN changed dramatically. Initial WLAN usage was dominated by Web traffic; our new trace shows significant increases in peer-to-peer, streaming multimedia, and voice over IP (VoIP) traffic. On-campus traffic now exceeds off-campus traffic, a reversal of the situation at the WLAN's initial deployment. Our study indicates that VoIP has been used little on the wireless network thus far, and most VoIP calls are made on the wired network. Most calls last less than a minute.

We saw greater heterogeneity in the types of clients used, with more embedded wireless devices such as PDAs and mobile VoIP clients. We define a new metric for mobility, the ``session diameter.'' We use this metric to show that embedded devices have different mobility characteristics than laptops, and travel further and roam to more access points. Overall, users were surprisingly non-mobile, with half remaining close to home about 98% of the time.

Sung Hoon Kim. **Greenpass RADIUS tools for delegated authorization in wireless networks.** Master's thesis, Dept. of Computer Science, Dartmouth College, June 2004. Available as Dartmouth Computer Science Technical Report TR2004-510.

Dartmouth's Greenpass project extends how public key cryptography can be used to secure the wireless LAN with a RADIUS (Remote Authentication Dial In User Service) server that is responsible for handling authentication requests from clients (called supplicants in the 802.1x authentication model). This thesis describes the design and implementation of the authentication process of Greenpass, specifically what decisions are made in determining who is granted access and how a small modification of already existing protocols can be used to provide guest access in a way that better reflects how delegation of authority works in the real world.

Greenpass takes advantage of the existing PKI to authenticate local Dartmouth users via X.509 identity certificates using EAP-TLS. We use the flexibility of SPKI/SDSI (Simple Public Key Infrastructure/Simple Distributed Security Infrastructure) authorization certificates to distribute the responsibility of delegating access to guests to certain authorized delegators, avoiding some of the necessary steps and paperwork associated with having a large centralized entity responsible for the entire institution. This thesis also discusses how our solution can be adapted to support different methods of guest delegation and investigates the possibility of eliminating the cumbersome central entity and administrative overhead traditionally associated with public key cryptography.

David Kotz, Calvin Newport, Robert S. Gray, Jason Liu, Yougu Yuan, and Chip Elliott. **Experimental evaluation of wireless simulation assumptions.** In Proceedings of the ACM/IEEE International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), October 2004.

All analytical and simulation research on ad hoc wireless networks must necessarily model radio propagation using simplifying assumptions. We provide a comprehensive review of six assumptions that are still part of many ad hoc network simulation studies, despite increasing awareness of the need to represent more realistic features, including hills, obstacles, link asymmetries, and unpredictable fading. We use an extensive set of measurements from a large outdoor routing experiment to demonstrate the weakness of these assumptions, and show how these assumptions cause simulation results to differ significantly from experimental results. We close with a series of recommendations for researchers, whether they develop protocols, analytic models, or simulators for ad hoc wireless networks.

New Research Papers (Continued)

Qun Li. Mobility and Communication in Sensor Networks. PhD thesis, Dept. of Computer Science, Dartmouth College, August 2004.

This thesis considered the duality between two important issues in sensor network research: communication and mobility. We build on the infrastructure of power-aware communication and global clock synchronization and show the duality between communication and mobility can be achieved to enhance each other's quality and efficiency. First, sensor network provides a way to augment the environment for a variety of problems, including mobility-related problems such as robot navigation. By shifting some burden of the problem to the sensor network augmented environment, the new information embedded in the environment that can be obtained by a user on spot and in real time can help to solve problems more efficiently and realistically. Second, mobility can serve to achieve communication since mobility is very common in everyday life. It is useful to use the controlled mobility of the specialized communication nodes and free natural mobility to guarantee communication, reduce power consumption, and increase network capacity.

To build an infrastructure for sensor network, we focused on two problems: power-aware communication and clock synchronization. We gave several communication protocols to conserve the energy in sensor network communication, both on the scale of the whole network and on a single node. We showed that by carefully designed routing protocol and fine-tuned sleep/wakeup node schedule, much energy can be conserved. We also designed several protocols for global clock synchronization. The most interesting one is diffusion-based clock synchronization, which is a fault-tolerant and localized protocol.

The duality between communication and mobility was shown as follows. First, we showed that communication can be achieved by controlled mobility and natural mobility. We used active trajectory change to obtain guaranteed message delivery. Then we demonstrated that natural mobility can be used to help communication to conserve energy and overcome disconnection. Second, we showed in navigation application that communication can assist mobility. We gave communication protocols to support user guidance in a sensor network, refined the protocols by considering reducing network searching space, and explored a mobility coordination problem: task assignment in robotic network applications.

Calvin Newport. Simulating mobile ad hoc networks: a quantitative evaluation of common MANET simulation models. Technical Report TR2004-504, Dept. of Computer Science, Dartmouth College, June 2004. Senior Honors Thesis.

Because it is difficult and costly to conduct real-world mobile ad hoc network experiments, researchers commonly rely on computer simulation to evaluate their routing protocols. However, simulation is far from perfect. A growing number of studies indicate that simulated results can be dramatically affected by several sensitive simulation parameters. It is also commonly noted that most simulation models make simplifying assumptions about radio behavior. This situation casts doubt on the reliability and applicability of many ad hoc network simulation results.

In this study, we begin with a large outdoor routing experiment testing the performance of four popular ad hoc algorithms (AODV, APRL, ODMRP, and STARA). We present a detailed comparative analysis of these four implementations. Then, using the outdoor results as a baseline of reality, we disprove a set of common assumptions used in simulation design, and quantify the impact of these assumptions on simulated results. We also more specifically validate a group of popular radio models with our real-world data, and explore the sensitivity of various simulation parameters in predicting accurate results. We close with a series of specific recommendations for simulation and ad hoc routing protocol designers.

Glenn Nofsinger and Keston Smith. Plume source detection using a process query system. In Defense and Security Symposium 2004 Proceedings, Bellingham, Washington, April 2004. SPIE.

A Process Query System (PQS) has the capability of filtering large volumes of real time data originating from a field of networked Physical Sensors. Modern air quality monitoring techniques such as Fourier Transform Infra-Red (FTIR) spectroscopy will eventually provide massively distributed real time contamination data at high fidelity. As large networks of these sensors are deployed, improved techniques of data retrieval and assimilation will be required. The case of detecting a diffusion event such as a hazardous chemical plume is considered. In this scenario, a plume model based on an Ensemble Kalman Filter (EnKF)is submitted to the PQS which manages multiple hypotheses explaining the current observations. The feasibility of such an application is demonstrated and results from preliminary simulations are presented.

Ronald Peterson and Daniela Rus. Interacting with sensor networks. In Proceedings of the IEEE 2004 International Conference on Robotics and Automation, May 2004.

We develop distributed algorithms for sensor networks that respond by directing a target (robot or human) through a region. The sensor network models the event levels sensed across a geographical area, adapts to changes, and guides a moving object incrementally across the network. We describe a device we call a Flashlight for interacting with the sensor field. This interaction includes collecting navigation information from the sensors in the local neighborhood, activating and deactivating specified areas of the sensor network, and detecting events in the sensor network. We report on hardware experiments using a physical sensor network consisting of Mote sensors.

Jue Wang, Guanling Chen, and David Kotz. A meeting detector and its applications. In MobiSys 2004 Workshop on Context Awareness, June 2004.

In this paper we present a context-sensing component that recognizes meetings in a typical office environment. Our prototype detects the meeting start and end by combining outputs from pressure and motion sensors installed on the chairs. We developed a telephone controller application that transfers incoming calls to voice-mail when the user is in a meeting. Our experiments show that it is feasible to detect high-level context changes with ``good enough'' accuracy, using low-cost, off-the-shelf hardware, and simple algorithms without complex training. We also note the need for better metrics to measure context detection performance, other than just accuracy. We propose several metrics appropriate for our application in this paper. It may be useful, however, for the community to define a set of general metrics as a basis to compare different approaches of context detection.

Jue Wang. Performance evaluation of a resource discovery service. Master's thesis, Dept. of Computer Science, Dartmouth College, October 2004. Available as Dartmouth Computer Science Technical Report TR2004-513

In a pervasive computing environment, the number and variety of resources (services, devices, and contextual information resources) make it necessary for applications to accurately discover the best ones quickly. Thus a resource-discovery service, which locates specific resources and establishes network connections as better resources become available, is necessary for those applications. The performance of the resource-discovery service is important when the applications are in a dynamic and mobile environment. In this thesis, however, we do not focus on the resource- discovery technology itself, but the evaluation of the scalability and mobility of the resource discovery module in Solar, a context fusion middleware. Solar has a naming service that provides resource discovery, since the resource names encode static and dynamic attributes. The results of our experiments show that Solar's resource discovery performed generally well in a typical dynamic environment, although Solar can not be scaled as well as it should. And we identify the implementation issues related to that problem. We also discuss experience, insights, and lessons learned from our quantitative analysis of the experiment results.

GRADUATES

Dr. Zack Butler, a postdoc with Daniela Rus and then a Postdoctoral Fellow at the Institute for Security Technology Studies, spent his time at Dartmouth focused on reconfigurable robotic systems and on sensor networks. Indeed, he was involved with the cows project described in the cover story. He is now an assistant professor of computer science at the Rochester Institute of Technology (RIT).

Guanling Chen recently completed his Ph.D. thesis, "Solar: Building A Context Fusion Network for Pervasive Computing", in which he built and evaluated a middleware framework to support context-aware applications in pervasive computing. Solar is flexible and allows applications to select distributed data sources and compose them with customized data-fusion operators into a directed acyclic information flow graph. Guanling is now an I3P Fellow at the Institute for Security Technology Studies at Dartmouth College and will join the University of Massachusetts (Lowell) beginning Fall 2005.

Nikita Dubrovsky graduated in June with an honors A.B. degree in computer science, based on his senior thesis, "Mobile Agents Simulation with DaSSF", which presents a simple mobile-agent simulation that can provide quick information on the performance and scalability of a generic information retrieval (IR) mobile-agent system under different network configurations. He is now at Appian Corp. in Vienna, VA.

Dr. Geoff (Guofei) Jiang spent several years as a postdoc and then senior research scientist at Dartmouth, working on many topics in mobile computing and computer security. He recently joined NEC Research in Princeton, where he leads the Robust and Secure System Group.

Qun Li recently completed his Ph.D. thesis, "Mobility and Communication in Sensor Networks", and is now an assistant professor of computer science at the College of William and Mary in Williamsburg, VA. His thesis considered the duality between two important issues in sensor network research: communication and mobility. It builds on the infrastructure of power-aware communication and global clock synchronization and shows how the duality between communication and mobility can enhance each other's quality and efficiency.

Cal Newport graduated in June with an honors A.B. degree in computer science, based on his senior thesis, "Simulating Mobile Ad Hoc Networks: A Quantitative Evaluation of Common MANET Simulation Models". His work, which explored the relationship between simulation and experimental results in ad hoc wireless networks, provided the basis for two papers recently presented at MSWiM. Cal is now a graduate student in computer science at MIT.

Jue Wang recently completed her M.S. thesis, "Performance Evaluation of a Resource Discovery Service", in which she evaluated the scalability and performance of the naming system in Solar. Solar is Guanling Chen's middleware that supports context-aware applications.

The Mistaken Axioms of Ad Hoc Wireless Network Research

All analytical and simulation research on ad hoc wireless networks must necessarily model radio propagation using simplifying assumptions. Based on a recent set of outdoor experiments with an implementation of real ad hoc network protocols, we provide a comprehensive review of six assumptions that are still part of many ad hoc network simulation studies:

0: The world is flat.
1: A radio's transmission area is circular.
2: All radios have equal range.
3: If I can hear you, you can hear me (symmetry).
4: If I can hear you at all, I can hear you perfectly.
5: Signal strength is a simple function of distance.

These axioms are commonly assumed in many papers about ad hoc networks, despite increasing awareness of the need to represent more realistic features, including hills, obstacles, link asymmetries, and unpredictable fading.

In a recent paper presented at MSWim2004, we use an extensive set of measurements from a large outdoor routing experiment to demonstrate the weakness of these assumptions, and show how these assumptions cause simulation results to differ significantly from experimental results. We include a series of recommendations for researchers, whether they develop protocols, analytic models, or simulators for ad hoc wireless networks. For the full paper, see http://cmc.cs.dartmouth.edu/papers/kotz:axioms.pdf. For a related paper detailing the performance of the MANET routing protocols, see http://cmc.cs.dartmouth.edu/papers/gray:compare.pdf.

About the CMC

The goal of the Center for Mobile Computing at Dartmouth College is to realize the potential for ubiquitous mobile devices and wireless communications to improve the way we live, the way we work, and the way we learn.

We have the opportunity to leverage Dartmouth's campus-wide wireless network, its group of experienced researchers, its residential campus with an innovative and creative student culture, its long tradition of pervasive deployment of cutting-edge technology and of technology in the classroom, and its local institutes for Security Technology (ISTS) and Information Infrastructure Protection (I3P). This combination makes Dartmouth College a unique environment for understanding the future, in which mobile computing becomes ubiquitous on university campuses, corporate campuses, and the consumer world.

The CMC is comprised of researchers from the Departments of Computer Science and Sociology and from the Thayer School of Engineering, including faculty, post-doctoral researchers, M.E. and Ph.D. students, and undergraduate students, and of staff from Dartmouth's Computing Services department. Participating faculty members have extensive experience in wireless networks, sensor networks, mobile agents, parallel and distributed computing, operating systems, information retrieval, robotics, signal processing, and sociology.

The Center's projects receive funding from the CMC industrial Partners, and federal funding from the Department of Homeland Security (through ISTS), the Defense Advanced Research Projects Agency (DARPA), the Office of Naval Research, and the National Science Foundation.

Center research facilities include campus-wide wired and wireless networks as well as a heterogeneous collection of computing systems. In effect, Dartmouth College is an extensive testbed with several thousand networked computers and active users.

Partnership

We invite corporations to become Partners of the CMC. There are clear benefits for partnerships with Dartmouth's Center for Mobile Computing. Partners have early access to advanced research that can lead to next-generation products and services. At the same time, the CMC benefits from a better understanding of the needs and direction of industry, helping to keep research relevant and driven by application needs.

Contact us if you are interested in being a partner at cmc@cs.dartmouth.edu

Benefits:

- Access to CMC students, making connections that may lead to future employment
- Access to wireless trace data
- Access to CMC faculty as consultants
- Early access to prototype systems
- Access to CMC labs and facilities, when appropriate.

Ultimately, each partnership leads to a host of benefits and to a relationship that can be customized to the needs and interests of the partner.

Current Partners

Apple

Cisco Systems

intel

NTT DoCoMo USA Labs

CMC Faculty and Staff

http://cmc.cs.dartmouth.edu/people/

Professor Denise Anthony, Department of Sociology

Professor Ted Cooley, Thayer School of Engineering

Professor George Cybenko, Thayer School of Engineering

Adjunct Professor Bob Gray, Department of Computer Science

Research Professor Tristan Henderson, Department of Computer Science

Professor David Kotz, Department of Computer Science

Research Professor Sue McGrath, Thayer School of Engineering

Professor Daniela Rus, Department of Computer Science

Professor Sean Smith, Department of Computer Science

Brad Noblet, Director of Technical Services, Peter Kiewit Computing Services

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