Project Final Report

June 2012

Award: DOE EPSCoR Award Number DE-FG02-04ER46136

Title: Ubiquitous Computing and Monitoring System (UCoMS) for Discovery and Management of Energy Resources

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Summary

The UCoMS research cluster has spearheaded three research areas since August 2004, including wireless and sensor networks, Grid computing, and petroleum applications. The primary goals of UCoMS research are three-fold: (1) creating new knowledge to push forward the technology forefronts on pertinent research on the computing and monitoring aspects of energy resource management, (2) developing and disseminating software codes and toolkits for the research community and the public, and (3) establishing system prototypes and testbeds for evaluating innovative techniques and methods. Substantial progress and diverse accomplishment have been made by research investigators in their respective areas of expertise cooperatively on such topics as sensors and sensor networks, wireless communication and systems, computational Grids, particularly relevant to petroleum applications.

Over the course of the research, the UCoMS team has amassed 38 journal articles published or accepted for publication, many in reputed professional journals. Additionally, major technical outcomes were delivered at various conferences and workshops, with a total of 85 articles included in their respective proceedings. Research and development outcomes, software codes and utilities/tools, and technical publications are posted on the UCoMS website, http://www.ucoms.org, for wide information dissemination and sharing. The UCoMS team initiated and continues to expand industrial and academic partners to facilitate technology transfer and to create a large knowledge pool for sharing. Collaborative work among investigators from participating institutions has established a multi-campus Grid testbed with a unified user-friendly portal developed for managing and steering job execution easily and efficiently. A wireless mesh network has been deployed, and it serves as the key building block for our integrated production site monitoring (PSM) system, which exhibits an end-to-end solution encompassing new techniques and software modules/tools developed to address important UCoMS technical challenges and requirements. Selected technical solutions and innovative approaches have been incorporated in the UCoMS testbeds for assessment and real-world evaluation.

The UCoMS team has secured eight new research grants and two infrastructure awards from NSF plus others from the industry and the State of Louisiana, with a total amount exceeding **$5.4M**, as detailed next. Since 2004, three UCoMS investigators have received the prestigious NSF CAREER awards and are conducting research activities pertinent to and expanding the scope of the UCoMS project, with each award ranging from $479,000 to $400,000. There have been four undergraduate students working on tasks relevant to UCoMS research, supported by the NSF Research Experiences for Undergraduates (REU) program.

The computation resources offered by the UCoMS Grid infrastructure meet the needs of large-scale reservoir simulation, data integration, and uncertainty assessment. Several challenging research topics related to Grid computing have been addressed, including scalable Grid resource discovery, user-friendly Grid interface design and implementation, efficient task execution on heterogeneous multi-cluster Grid environments, and large Grid storage management. UCoMS has also investigated into stochastic model inversion using massively parallel reservoir simulators and the Ensemble Kalman Filter in a Grid environment. These tools can efficiently integrate diverse geophysical, geologic, geostatistical, and field production data for improved uncertainty analysis and risk production forecasting using an ensemble of large, heterogeneous flow models.

Accomplishment Highlights

- *Major Grants Received.* UCoMS investigators Hongyi Wu (in 2004) and Dmitri Perkins (in 2005) received NSF CAREER awards providing five-year funding to carry out research on wireless communications. Gabrielle Allen *et al*. won one NSF grant of $220,000 in 2006 to develop on a general DDDAS framework. Magdy Bayoumi received an NSF-CRI grant of $298,848 on MEMS Integration, in June 2006. Tevfik Kosar and Gabrielle Allen secured an MRI grant of $957,678 in August 2006 from NSF on development of PetaShare. In 2008, Hongyi Wu and Nian-Feng Tzeng received a core research grant of $366,000 from the CNS Division, NSF, for a 3-year project. Additionally, Hongyi Wu and Magdy Bayoumi received an NSF MRI grant of $500,000 in 2008 for acquiring a wireless nanonetworks integration and emulation system. In 2009, Tevfik Kosar received the prestigious NSF CAREER award and another NSF award of $495,514, while Gabrielle Allen secured an NSF award of $299,447. Also, Tevfik Kosar and Gabrielle Allen received an NSF infrastructure award of $400,000. In 2010, C. White and J. M. Lorenzo received one 3-year grant of $300,000, from Shell E&P Technology Company, whereas C. White and Y. Tyagi secured another 3-year grant of $300,000 from Shell E&P Technology Company.
- *Outstanding Awards.* UCoMS investigator, Ed Seidel, received the prestigious **2006 Sidney Fernbach Award** during IEEE/ACM Supercomputing (SC|06) in Tampa, Florida on November 15, 2006. Separately, Magdy Bayoumi, was elected in November 2006 as Vice President - Conferences, of the IEEE Circuits and Systems (CAS) Society, from which he received Meritorious Service Award in May 2009.
- *Computational Grid and UCoMS Testbeds*. A computational Grid had been established as an important infrastructure milestone, and it included computer clusters located at two participating institutions, UL at Lafayette and LSU, to enable the empirical evaluation of new Grid computing techniques and petroleum applications pursued under this project. Two UCoMS testbeds were also established for evaluating new solution approaches we considered, including the production site monitoring (PSM) integrated system and the close-loop solution (CLS). PSM consists of (1) a 700MHz WiFi-based wireless mesh network developed and deployed under outdoor environments on the ULL campus and (2) a wireless sensor network (WSN) built with Telosb sensor nodes for evaluating energy-efficient distributed signal processing algorithms we devised, in terms of such metrics as the computation speedup and the network lifetime. The WSN is aimed for data gathering and aggregation from production fields, and streams data wirelessly over the mesh network to the computational Grid for storage and processing by means of application software being developed and to be deployed. PSM has been built upon technical blocks created by UCoMS investigators, including the unified user-friendly portal interface, a wireless mesh network testbed, a computational Grid, and application codes and utilities. Meanwhile, we ran ensembles of models with over 10^6 blocks in support of our CLS, using as many as 10^4 processors on multiple clusters, in a high-performance, scalable parallel framework, with EnKF adapted for parallel computation to manage large ensembles of finely gridded models.

- *Collaborative Partners.* UCoMS established collaboration with two industrial partners (1) wireless data acquisition for Tetra Production Testing Services (URL: http://www.tetratec.com) and (2) cost-effective sand detection system with NSI Upstream (URL: http://www.nsiupstream.com/). In addition, collaboration with an LSU campus unit (Coastal Studies Institute of the Department of Oceanography) was formed for our access to a 4×8 *m* experimental sand wave tank for conducting diverse experiments.
- *Demonstrations and Result Dissemination.* The UCoMS team participated in national technical exhibitions persistently during the course of its research duration for demonstrating its research and development solutions and prototypes, participating in SC|05, SC|06, SC|07, SC|08, SC|09, SC|10 with its demonstration booth, which drew considerable visitors, gave wide publicity to the research community and National Labs' participants, and helped to initiate collaborative opportunities In addition, the research team also took part in such technical exhibits as TechSouth 2005 and TechSouth 2006. Such participation helped to disseminate UCoMS research and application outcomes to diverse audience and the public widely.
- *Research Publications and Outcomes.* Our research team has made substantial technical contributions, publishing many articles in reputed journals and delivering research results in various professional conferences and forums, as posted in our UCoMS website, http://www.ucoms.org. These research publications span all UCoMS technical thrusts on sensor networks and RFID systems, wireless communication and networks, Grid computing, and applications, and they are detailed below.

Key Technical Results/Milestones Achieved

(1) Sensor Networks and RFID Systems

- *Resource Optimization*. To enable efficient cooperation and resource utilization in wireless sensor networks, we have proposed algorithms based on game theory for stimulating collaboration among non-cooperative nodes to achieve efficient resource optimization.
- *Localization*. We have developed a fine-grain triangulation algorithm based on nodal connectivity only for efficient localization and geographic routing in wireless sensor networks. Additionally, an efficient and practical algorithm for 3-D localization in underwater sensor networks has been introduced, with a high localizable rate, good accuracy, and low computational overhead.
- *Efficient Collision Resolution*. We have extended our research on medium access control in conventional wireless mesh networks to the emerging RFID system, and proposed an efficient tag arbitration algorithm which achieves low delay and energy consumption.
- *Sensor Networks for Scene Surveillance and Object Tracking.* Our scene surveillance approach makes use of a network of camera sensors, each of which has a wide viewing angle to capture the raw video stream for analysis and serves as an agent to deal with a region of interest. We have also developed low-complexity techniques for object detection and tracking in support of our scene-surveillance framework for various automated surveillance applications.
- *Energy Reduction for Sensor Networks.* We have investigated into an energy reduction framework by reducing the number of queries for the sensor energy status, dealing with two types of energy reading information aggregation.
- *Signal Processing over Wireless Sensor Networks.* Scalable numerical processing algorithms were developed for the first time on resource-constrained sensor nodes in wireless sensor networks, with the implemented results obtained using a real sensor network.

- *Accurate Localization based on RFID Gear.* RFID support for localization, aiming to pinpoint an object (i.e., a reader) in a 3-dimensional space, has been developed, with two localization schemes considered and contrasted.

(2) Wireless Communication and Networks

- *Self-Configurable Positioning Technique*. We have developed the most effective and self-configurable GPS-free positioning technique for wireless networks known so far, making use of several chosen network nodes as landmarks. All network nodes calculate their coordinates according to the landmarks.
- *Enhancement to MAC Protocols.* A novel MAC protocol, called SYN-MAC, has been devised for synchronized multi-hop wireless networks, with distributed, simple, robust, efficient, fair, and QoS-capable attributes. It effectively resolves channel contention and deals with the hidden station problem in wireless networks. We have also developed a new enhancement called Distributed and Fair Access (DFA) protocol, proposed for multihop wireless networks, with its performance analyzed and evaluated using extensive simulation.
- *Prioritized Medium Access Control*. We have proposed a Prioritized Medium Access Control (P-MAC) protocol, which differentiates packets in multiple service classes based on their priority levels to achieve different levels of service.
- *Cross-Layer Design and Association in Wireless Networks*. We arrived at a single-input-single-output feedback control system for cross-layer design of wireless networks, making use of our experimental and regression analytic study to quantify the interactive effects of network components. In addition, a Cross-Layer Association (CLASS) scheme has been carried out for IEEE 802.11-based multi-hop WMNs to enable fast identification of a mesh access point for improved performance.
- *Backhaul-Aided Seamless Handoff*. We have investigated a backhaul-aided seamless handoff (BASH) scheme for wireless mesh networks (WMNs) to let a mobile station directly access the backhaul channel and broadcast probe requests to neighboring mesh routers. BASH achieves a speedy handoff in support of real-time applications.
- *Minimum-Cost Data Delivery in Wireless Networks*. We have devised an efficient minimum-cost data delivery algorithm based on linear programming (LP), with various constraints taken into consideration.
- *Wireless Network Testbed Investigation and Deployment.* We have pursued a system-level adaptive model-based self-controller for multi-hop wireless networks. The proposed self-controller determined a set of controllable factor values to maximize system performance or satisfy specific performance. We have also deployed a wireless mesh testbed based on 700 MHz WiFi gear for evaluation, with experimental results collected and compared with those with conventional 2.4GHz WiFi gear.
- *Scalability Evaluation of Ad Hoc Routing*. We combined statistical design of experiments methods, empirical modeling techniques, and a newly proposed performance measure, to arrive at a new scalability analysis framework for ad hoc routing protocols.
- *Wireless Communication Performance Enhancement*. We have pursued network coding for wireless mesh networks, called XOR-Top, which exhibits improved network throughput of up to 150% when compared with its earlier counterpart. Also, a backhaul-aided seamless handoff (BASH) scheme for wireless mesh networks was proposed, with experimental results

show that BASH can support real-time applications even in the presence of connection handoffs.

- *Distributed Cognitive Radio Networks.* We have dealt with decentralized asynchronous ad hoc cognitive radio networks, developing a spectrum management scheme for alleviating the negative impact of inherent inaccuracy in spectrum sensing of cognitive radios on network performance.

(3) Grid Computing

- *ResGrid Toolkit and UCoMS Grid Portal.* We developed the ResGrid toolkit, which adopts a load balancing strategy to efficiently submit reservoir simulation runs across a computational Grid, with Condor-G used to provide job management and queuing control. In addition, we implemented the Grid portal for reservoir uncertainty analyses, based on GridSphere technology, which was the de facto standard for Grid portals.
- *Execution Checkpointing in Mobile Grids.* Collaborative hosts for job execution in mobile Grids disseminate checkpointing files to a number of other mobile hosts (MHs) for storage so that recovery can better succeed. We have devised and evaluated an effective and robust dissemination arrangement mechanism, following our Reliability Driven (ReD) method, to achieve significant gains in comparison to earlier known data dissemination techniques.
- *Peer-to-Peer Resource Discovery*. A fast and scalable ReD mechanism, dubbed FaSReD, was pursued in support of multi-attribute range queries for resource discovery in heterogeneous Grids. FaSReD searches over the prefix hash tree (PHT) with low traffic overhead to exhibit efficient resource discovery and high scalability.
- *Energy Consumption Modeling.* We have introduced a run-time energy consumption prediction model for servers, making use of hardware performance counters and on-chip sensor readings. Our energy model takes into account processor power, bus activities, and system ambient temperature to arrive at the Chaotic Attractor Predictor (CAP) for more accurate energy consumption prediction in real-time.
- *Grid Workflow and Dataflow*. We developed Pelecanus for closed-loop applications and implemented end-to-end workflows for the EnKF stochastic inversion package, with two numerical reservoir flow simulators, UTChem and BlackOil.

(4) Applications

- *Real-Time Production and Drilling Problems Identification*. We have developed an effective method to diagnose the liquid loading problem for better predicting abnormal production declines and also a mathematical model to enable pressure instability analyses based on real-time drilling pressure readings.
- *Reservoir Simulation Improvement.* We have improved reservoir simulation performance chiefly via distributing actual Kalman gain computation for better memory utilization and decreased data transmission requirements and adopting better data transmission formats. Two speedy reservoir simulation techniques were developed, with the numerical testing outcomes confirming their speedups exceeding 100.
- *Multilateral and Horizontal Wells.* A more accurate method for predicting composite IPR of multilateral wells was developed, able to better estimating the well production rate. We also devised an analytic model for inflow performance prediction of horizontal wells.

- *Real-Time Model Inversion and Optimization.* A new hybrid EnKF method has been formulated, with its superior efficiency, stability, and accuracy verified for both idealized linear, Gaussian cases and nonlinear, non-Gaussian flow models. We have also established efficient simulation frameworks for managing data communication in large-scale and distributed computation by employing PetaShare to let the underlying infrastructure manage the low-level data handling issues and SAGA (Simple API for Grid Applications).
- *Physical Experiment, Flow Modeling, and Seismic Data Processing.* We have gathered pressure, rate, and seismic data from our meter-scale flow and seismic experiment. The data are moved from laboratory data acquisition computers to PetaShare, where data processing, flow modeling, and model inversion are performed. In addition, the BlackOil model has been enhanced for more diverse scenarios including thermally driven convection, making it useful for geothermal modeling. Computational efficiency has been improved by dual time-stepping, better preconditioning, and more rigorous stability controls.

Significant Findings and Accomplishments

(1) Sensor Networks and RFID Systems

- *Resource Optimization*. This work develops distributed stimulation algorithms for mobile wireless networks, which not only enables cooperation among selfish nodes but also achieves efficient resource utilization and optimization in the entire network. Two approaches based on Nash game theory have been proposed, as summarized in the following papers:
  - T. Ning, Z. Yang, X. Xie, and Hongyi Wu, "Incentive-Aware Data Dissemination in Delay-Tolerant Mobile Networks," *Proceedings of 8th IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks* (*SECON*), June 2011.
  - X. Xie and Hongyi Wu, "Bargain-Based Stimulation Mechanism for Intermittently Connected Selfish Participatory Sensing Networks," submitted to *IEEE Transactions on Mobile Computing*.
- *Localization*. In this work, we have pursued a distributed algorithm for triangulation in an arbitrary sensor network, with no constraints on communication models. We prove its correctness in 2D, and further extend it to sensor networks deployed on 3D open and closed surfaces. Separately, localization in wireless sensor networks deployed on underwater surfaces has been addressed as well. Given its unique difficulty for 3D underwater surfaces, we adopted a layered approach to enhance localizability of such surface sensor networks. Sensor-based experiments and large-scale simulation were carried out to evaluate the proposed localization algorithm, with numeric results confirming that the proposed algorithm can effectively improve the localizable rate and achieve low location errors and computational overhead. The results of this research topic are summarized in the following papers:
  - H. Zhou, Hongyi Wu, S. Xia, M. Jin, and N. Ding, "A Distributed Triangulation Algorithm for Wireless Sensor Networks on 2D and 3D Surface," *Proceedings of 30th Annual Joint Conference of IEEE Computer and Communications Societies* (*IEEE INFOCOM*), April 2011.
  - Y. Zhao, Hongyi Wu, M. Jin, and S. Xia, "Localization in 3D Surface Sensor Networks: Challenges and Solutions," *Proceedings of 31st Annual IEEE International Conference on Computer Communications* (IEEE *INFOCOM*), pp. 55-63, March 2012
- *Efficient Collision Resolution.* By leveraging our earlier research results in collision resolution in wireless communications, we have developed a self-learning Smart Trend-Traversal (STT)

protocol for tag arbitration, which effectively reduces the collision overhead occurred in large-scale RFID systems. STT, a Query Tree-based scheme, dynamically issues queries according to the adaptively learned tag density and distribution, therefore significantly reducing delay and energy consumption in comparison with the existing tree-based and Aloha-based protocols. This research has been reported in the following paper submitted to a journal for possible publication:

- L. Pan and Hongyi Wu, "PTS: A Probability-based Tag Selection Algorithm for RFID Systems with Recurring Reading," *Proceedings of International Conference on Computer Communications and Networks* (*ICCCN*), August 2009.
- L. Pan and Hongyi Wu, "STT: A Smart Trend-Traversal Tag Arbitration Protocol for Large RFID Systems," submitted to *IEEE Transactions on Wireless Communication*, under a minor revision.

■ *Sensor Networks for Scene Surveillance and Object Tracking*. Our approach to scene surveillance makes use of a network of sensors, each of which serves as an agent to deal with a region of interest. Each camera sensor has a wide viewing angle to capture the raw video stream for analysis. A region agent segments an image using the foreground mask, with each segment sent to an object agent (spawned by the region agent) for processing and tracking. The object agent is responsible for updating the object model based on information subtracted from several frames. When an object approaches the border of the area monitored by a region agent, the agent communicates with another proper agent to pass along its carried information. The region agent negotiates a proper handoff of moving objects leaving its area with its neighbors. We have also established an object-tracking and scene-surveillance framework for various automated surveillance applications, developing low-complexity techniques for object detection and tracking, and testing visual and infrared data fusion algorithms built on dual-tree complex wavelet transform techniques for information extraction from heterogeneous video sources. The developed framework includes object processing units, an object detection module, and a multi-agent tracking system for scene understanding. Simulation results have demonstrated the robustness and accuracy of our developed tracking algorithm. Separately, a fast multimodal automatic image registration algorithm has been devised, aiming to handle the alignment of IR and visible images. Research findings of this research topic can be found in articles listed below:

- R. Aguilar-Ponce, A. Kumar, J. Tecpanecatl-Xihuitl, and Magdy Bayoumi "Automated Object Detection and Tracking for Intelligent Visual Surveillance based on Sensor Network," *Artificial Intelligence and Integrated Intelligent Information Systems: Emerging Techniques and Applications* (as a book chapter), Idea-Group Press, 2006.
- R. Aguilar-Ponce, A. Kumar, J. Tecpancatl-Xihuitl, and Magdy Bayoumi, "A Network of Sensors Based Framework for Automated Visual Surveillance," *Journal of Networks and Computer Applications, Elsevier*, vol. 30, no. 3, August 2007, pp 1244-1271.
- R. Aguilar-Ponce, A. Kumar, J. Tecpancatl-Xihuitl, and Magdy Bayoumi, "Autonomous Decentralized Systems-Based Approach to Object Detection in Sensor Clusters" *IEICE Transactions on Communication Systems, IEICE/IEEE Joint Special Section on Autonomous Decentralized Systems*, vol. E88-B, pp. 4462-4469, Dec. 2005.
- R. Aguilar-Ponce, J. Tessier, A. Baker, J. Das, C. Emmela, J. Tecpanecatl-Xihuitl, A. Kumar, and Magdy Bayoumi, "Real-Time VLSI Architecture For Detection Of Moving Objects Using Wronskian Determinant," *Proceedings of IEEE International Midwest Symposium on Circuits and Systems*, Aug. 2005.
- R. Aguilar-Ponce, A. Kumar, J. Tecpancatl-Xihuitl, and Magdy Bayoumi, "An Architecture for Automated Scene Understanding," *Proceedings of IEEE International Workshop on Computer Architecture for Machine Perception*, July 2005.

- M. Ghantous, S. Ghosh, and Magdy Bayoumi, "A Gradient-Based Hybrid Image Fusion Scheme Using Object Extraction," *Proceeding of 15th IEEE International Conference on Image Processing* (*ICIP 2008*), October 2008, pp. 1300-1303.
- M. al-Najjar, S. Ghosh, and Magdy A. Bayoumi, "A Hybrid Technique for Object Detection," *Proceedings of IEEE International Symposium on Circuits and Systems*, May 2009, pp. 936-939.
- M. Al-Najjar, S. Ghosh, and Magdy A. Bayoumi, "Robust Object Tracking Using Correspondence Voting for Smart Surveillance Visual Sensing Nodes," *Proceedings of IEEE Int'l Conference on Image Processing* (*ICIP '09*), November 2009.
- M. Ghantous, S. Ghosh, and Magdy A. Bayoumi, "A Multi-modal Automatic Image Registration Technique based on Complex Wavelets," *Proceedings of IEEE Int'l Conference on Image Processing* (*ICIP '09*), November 2009, pp. 173-176.

- *Energy Reduction for Sensor Networks.* Our energy reduction framework aims to reduce the number of queries for the sensor energy status dispatched by cluster heads. Two types of information aggregation with respect to energy readings are possible: range-based and location-based ones. We have derived in detail the most desirable rate of query dispatching.
  - M. Bhattacharyya, A. Kumar, and Magdy Bayoumi, "A Framework for Assessing Residual Energy in Wireless Sensor Network," *International Journal of Sensor Networks*, vol. 2, 2007, pp. 256-272.
  - M. Bhattacharyya, A. Kumar, and Magdy Bayoumi, "Design and Analysis of Energy Reference Metric in a Cluster Based Wireless Sensor Network," *Proceedings of IEEE International Conference on Circuits and Systems for Communications* (*ICCSC '06*), July 2006.

- *Signal Processing over Wireless Sensor Networks.* This work aims to develop scalable numerical computing applications on resource-constrained sensor nodes for signal processing in wireless sensor networks. Distributed and parallel signal processing often use numerical methods, like LU/QR decomposition and SVD, as the core numerical solvers for large 2D FIR filters, Kalman filtering, IIR filtering, and 2D convolution, basic to signal processing. We have developed an effective data and code-scheduling scheme for LU decomposition, FFT and parallel matrix computations on wireless sensor nodes, with good scalability. Meanwhile, a framework for task scheduling and mapping onto WSN nodes has been developed for overall network life extension. Our framework includes (1) an integer non-linear programming formulation for task allocation, (2) a heuristic task mapping based on the proposed formulation, (3) a user-friendly, scalable simulator for evaluation. Utilizing our framework, a WSN may extend its lifespan by up to 390%, as described in the last article below.
  - S. Abdelhak, J. Tessier, S. Ghosh, and Magdy Bayoumi, "Block-LU Decomposition on Wireless Sensor Networks," *Proceedings of 51st IEEE International Midwest Symposium on Circuits and Systems* (MWSCAS 2008**),** August 2008.
  - S. Abdelhak, S. Ghosh, and Magdy Bayoumi, "Analysis of MAC Protocols for Low-Energy Signal Processing on Wireless Sensor Networks," *Proceedings of 51st IEEE International Midwest Symposium on Circuits and Systems* (MWSCAS 2008**),** August 2008.
  - S. Abdelhak, S. Ghosh, and Magdy Bayoumi, "Scalable and Energy-Aware Distributed Block-Based LU Decomposition on Wireless Sensor Networks," *Proceedings of 12th Annual Workshop on High Performance Embedded Computing* (*HPEC 2008*), September 2008, pp. 52-53.

- M. Ghantous, S. Ghosh, and M. Bayoumi, "A Gradient-Based Hybrid Image Fusion Scheme Using Object Extraction," *Proceedings of 15th IEEE International Conference on Image Processing* (*ICIP 2008*), October 2008, pp. 1300-1303.
- A. Abdelgawad, S. Abdelhak, S. Ghosh, and Magdy Bayoumi, "A Low-Power Multiplication Algorithm for Signal Processing in Wireless Sensor Networks," *Proceedings of 52nd IEEE Int. Midwest Symposium on Circuits and Systems* (*MWSCAS* 2009), pp.695-698, August 2009.
- S. Abdelhak, S. Ghosh, and Magdy Bayoumi, "Resouce-Aware Distributed Split Radix FFT on Wireless Sensor Networks," *Proceedings of 13th Annual Workshop on High Performance Embedded Computing* (*HPEC 2009*), September 2009.
- S. Abdelhak, R. Chaudhuri, C. Gurram, S. Ghosh, and Magdy Bayoumi, "Energy-aware Distributed QR Decomposition on Wireless Sensor Networks," *The Computer Journal*, special issue on Agent Technologies for Sensor Networks**,** 2010.

■ *Accurate Localization based on RFID Gear***.** Aiming to pinpoint an object in a 3-dimensional space, we have developed the very first range-free localization using only RFID tags without other devices or sensors, avoiding the need of distance estimation according to received wireless signal strength (known to be notoriously inaccurate) or phase difference (being complicated). Two localization schemes are considered and contrasted, and they both are shown to yield good accuracy, with a better one able to achieve the localization error as small as 0.07 ft and being more flexible in placing reference tags. Details of our developed 3-D localization are reported in the following papers:

- C. Wang, Hongyi Wu, and Nian-Feng Tzeng, "RFID-Based 3-D Positioning Schemes," *Proceedings of 26th Annual IEEE Conference on Computer Communications* (*IEEE INFOCOM '07*), May 2007.
- J. Maneesilp, C. Wang, Hongyi Wu, and Nian-Feng Tzeng, RFID Support for Accurate 3-Dimensional Localization," accepted in March 2012 for publication in *IEEE Transactions on Computers*.
- L. Pan and Hongyi Wu, "Smart Trend-Traversal: A Low Delay and Energy Tag Arbitration Protocol for Large RFID Systems," *Proceedings of 28th Annual Joint Conference of the IEEE Computer and Communications Societies* (*INFOCOM*), mini-conference, pp. 2571-2575, April 2009.

(2) Wireless Communication and Networks

■ *Self-Configurable Positioning Technique*. Under our self-configurable positioning technique, landmark nodes in a given wireless multi-hop network estimate the distances between each node pair by a Euclidean distance estimation model before establishing the coordinates for landmarks by minimizing an error objective function. Other nodes then calculate their coordinates according to the landmarks. The computing time for coordinate establishment is in the order of milliseconds, acceptable to most sensor network applications. Research findings are included in the following journal article:

- Hongyi Wu, C. Wang, and Nian-Feng Tzeng, "Novel Self-Configurable Positioning Technique for Multi-Hop Wireless Networks," *IEEE/ACM Transactions on Networking*, vol. 13, no. 3, pp. 609-621, June 2005.

■ *Enhancement to MAC Protocols*. Our devised novel MAC protocol, SYN-MAC, permits priority channel access and QoS support to allow selected users to conduct critical communications. An analytic model based on the queuing theory has been established for its performance evaluation. Separately, we have investigated a Distributed and Fair Access (DFA) protocol, for multihop

wireless networks, carrying out numerical analysis and modeling of the behavior of DFA. Our extensive simulation results verify that DFA demonstrates superior performance.

- Hongyi Wu, A. Utgikar, and Nian-Feng Tzeng, "SYN-MAC: A Distributed Medium Access Control Protocol for Synchronized Wireless Networks," *Mobile Networks & Applications: The Journal of Special Issues on Mobility of Systems, Users, Data and Computing*, Springer, vol. 10, no. 5, pp. 627-637, Oct. 2005.
- L. Pan and Hongyi Wu, "Performance Evaluation of the SYN-MAC Protocol in Multihop Wireless Networks," *Proceedings of International Conference on Computer Communications and Networks* (*ICCCN '07*), August 2007.
- X. Cao, L. Pan, and Hongyi Wu, "Enhanced Synchronized Medium Access Control Protocol for Wireless Ad Hoc Network," *Proceedings of International Conference on Computer Communications and Networks* (*ICCCN '07*), August 2007.
- L. Pan, X. Cao, and Hongyi Wu, "Design and Modeling a Distributed and Fair Access MAC Protocol (DFA) for Multihop Wireless Networks," *IEEE Transactions on Wireless Communication*, vol. 8, pp. 2434-2442, May 2009.
- L. Pan, Hongyi Wu, and Nian-Feng Tzeng, "An Efficient and Scalable Prioritized MAC Protocol (PMAC) for Backbone Communication in Wireless Sensor Networks," *Proceedings of Third International Conference on Sensor Technologies and Applications* (*SENSORCOMM*), June 2009.
- S. Xia and Hongyi Wu, "A CDMA-Based Approach for Highly Efficient Medium Access Control in Mesh Wireless Networks," *Proceedings of 10th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks* (*WoWMoM*), June 2009.

- *Prioritized Medium Access Control*. We have proposed a Prioritized Medium Access Control (P-MAC) protocol following the binary count down approach, in order to differentiate packets in multiple Service Classes (SC's) based on their priority levels, thus providing different levels of service. This is the first attempt to implement such an algorithm for service differentiation and to support absolute prioritization in distributed wireless networks, which cannot be achieved by any existing MAC protocols (such as IEEE 802.11e). We proved the service time of P-MAC to approximate exponential distribution, and provided solutions on how to estimate the service rates. We analyzed both preemptive and non-preemptive schemes. P-MAC still maintains an extremely stable and high channel throughput, ever under heavy load. As a key outcome of this research, the proposed analytic model, particularly the unique and accurate approach for calculating the packet dropping probability in each service class, provides a useful guideline for analyzing other service differentiation protocols in the future. Research findings are included in the following article:

  - Y. Li, Hongyi Wu, Nian-Feng Tzeng, Dmitri Perkins, and Magdy Bayoumi, "MAC-SCC: A Medium Access Control Protocol for Mobile Ad Hoc Networks," *IEEE Transactions on Wireless Communications*, vol. 5, pp. 1805-1817, July 2006.

- *Cross-Layer Design and Association in Wireless Networks*. Our cross-layer design approach was derived according to our experimental and regression analytic study, for quantifying the interactive effects of network components, developing approximate functions, and optimizing system performance over a wide range of scenarios. Separately, our proposed CLASS (Cross-Layer Association) uses an end-to-end airtime cost metric for MAP determination, considering the frame error rate for various packet sizes, the available bandwidth on the access link after the association of the new MS, and the asymmetric uplink and downlink transportation costs on the backhaul. Experimental results show that CLASS can identify the MAP which yields the highest end-to-end network performance for MSs after their associations. Important research findings related to this research topic are included in the following articles:

- M. Totaro and Dmitri Perkins, "Statistical Design of Experiments for Analyzing Mobile Ad Hoc Networks," *Proceedings of ACM/IEEE International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems,* Oct. 2005, pp. 159-168.
- Y. He and Dmitri Perkins, "Design and Implementation of CLASS: a Cross-Layer ASSociation Scheme for Wireless Mesh Networks," *Proceedings of IEEE Conference on Computer Communications (INFOCOM) Workshops*, pp. 1-6, March 2010.

- *Backhaul-Aided Seamless Handoff*. Our proposed Backhaul-Aided Seamless Handoff (BASH) scheme takes advantage of the wireless backhaul feature of WMNs, allowing a mobile station (MS) to directly access the backhaul channel and to broadcast probe requests to neighboring mesh routers. After the probe broadcast, the MS is able to switch back to its primary communication channel, resuming its ongoing communication without waiting for the probe responses. The mesh router to which the MS is currently associated collects the probe responses and selects the new mesh router on behalf of the mobile station. The experimental results show that BASH achieves an average Layer-2 handoff of 8.9ms, able to support real-time applications during the handoff. Our research findings on MASH have been included in the following paper:
  - Y. He and Dmitri Perkins, "Achieving Seamless Handoffs via Backhaul Support in Wireless Mesh Networks," *Springer Telecommunication Systems Journal: Special Issue on Mobile Computing and Networking Technologies*, October 2010.
- *Minimum-Cost Data Delivery in Wireless Networks*. An important optimization issue in integrated wireless networks is how to minimize the overall communication cost by intelligently utilizing the available heterogeneous wireless technologies while at the same time meeting the quality of service requirements of mobile users. In this research, we first identified the cost minimization problem to be NP-hard. We then presented an efficient minimum-cost data delivery algorithm based on linear programming (LP), with various constraints such as channel bandwidth, link costs, delay budgets, and user mobility taken into consideration. Extensive simulations were carried out to evaluate the proposed cost minimization scheme. Our results show that the proposed LP approach can effectively reduce the overall communication cost, with small overhead (< 3%) for signaling, computing, and handoff. Research findings are included in the following journal article:
  - H. Chen, Hongyi Wu, S. Kumar, and Nian-Feng Tzeng, "Minimum-Cost Data Delivery in Heterogeneous Wireless Networks," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 6, pp. 3511-3523, Nov. 2007.
- *Wireless Network Testbed Investigation and Deployment.* We have investigated the feasibility of a system-level adaptive model-based self-controller that can manage the values of controllable factors in multi-hop wireless networks. Given the network state, a proposed self-controller should determine a set of controllable factor values which maximize system performance or satisfy specific performance requirements. We identified the key design issues and developed a design to demonstrate the feasibility of a system-wide feedback controller based on two empirical modeling techniques: regression and artificial neural networks, as detailed in the next two articles. A wireless mesh testbed based on 700 MHz WiFi gear was deployed and evaluated under both indoor and outdoor environments, with experimental outcomes demonstrating that such a mesh network exhibits significantly larger transmission ranges and better penetration ability likely to boost its performance. Results of this research topic are published in the following articles:
  - A. Moursy, I. Ajbar, Dmitri Perkins, and Magdy Bayoumi, "Empirical Model-based Adaptive Control of MANETs," *Proceedings of IEEE Workshop on Automated Network Management* (in conjunction with IEEE INFOCOM), April 2008.

- A. Moursy, I. Ajbar, Dmitri Perkins, and Magdy Bayoumi, "Building Empirical Models of Mobile Ad Hoc Networks," *Proceedings of SCS/IEEE Int'l Symposium on Performance Evaluation of Computer and Telecommunications Systems*, July 2007.
- Y. He, V. Nguyen, Dmitri Perkins, and Nian-Feng Tzeng, "Exploring 700MHz WiFi-Based Wireless Mesh Networking," *Proceedings of 10th ACM International Symposium on Mobile Ad Hoc Networking and Computing* (*MobiHoc*), pp. 349-350, May 2009.
- B. Huang, Y. He, and Dmitri Perkins, "Investigating Deployment Strategies for Multi-radio Multi-channel Wireless Mesh Networks," *Proceedings of IEEE International Conference on Wireless and Mobile Computing, Networking and Communications* (*WiMOB*), pp.147-153, Oct. 2009.

- *Scalability Evaluation of Ad Hoc Routing*. We have proposed S-Box, a "blackbox" type scalability analysis framework, by combining statistical design of experiments (DOE) methods, empirical modeling techniques, and a newly proposed performance measure, called the *scalability index*. The index is able to quantify the overall system and protocol scalability by aggregating the values of multiple individual metrics into a single scalar value. For example, given a specific deployment scenario, S-Box can be used to (1) determine the routing protocol that achieves the best overall scalability among a set of candidate protocols and (2) determine how to adjust parameter values (e.g., number of RREQ retries) of a routing protocol to achieve enhanced scalability performance
  - Y. He, Dmitri Perkins, and B. Huang, "S-Box: A Scalability Analysis Framework for Wireless Multi-hop Routing Protocols," *Proceedings of IEEE Symposium on Computers and Communications*, July 2008.
  - I. Ajbar and Dmitri Perkins, "A Performance Index for Evaluating Multi-hop Wireless Networks," *Proceedings of IEEE International Conference on Computer Communications and Networks*, Aug. 2007.

- *Wireless Communication Performance Enhancement*. We have pursued network coding for wireless mesh networks, called XOR-Top, which relies on local topology information only, uses bitwise XOR for packet coding, and proactively attempts to decode coded packets stored in node buffers. Compared with its earlier counterpart, XOR-Top exhibits improved network throughput of up to 150%. It also leads to significant reduction in the average end-to-end packet latency. Meanwhile, we have proposed BASH – a backhaul-aided seamless handoff scheme for wireless mesh networks. Experimental results show that BASH achieves an average Layer-2 handoff of 8.7ms, able to support the real-time applications during the handoff. Separately, we have devised a cross-layer hop-by-hop congestion control scheme for TCP performance improvement in multi-hop wireless networks. It achieves up to 70% higher throughput than TCP-Reno according to our simulation results.
  - R. Prasad, Hongyi Wu, Dmitri Perkins, and Nian-Feng Tzeng, "Local Topology Assisted XOR Coding in Wireless Mesh Networks," *Proceedings of Second International Workshop on Wireless Mesh and Ad Hoc Networks* (*WiMAN 2008*, in conjunction with IEEE ICDCS-28), June 2008, pp. 156-161.
  - Y. He and Dmitri Perkins, "BASH: A Backhaul-aided Smooth Handoff Scheme for Wireless Mesh Networks," *Proceedings of IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks* (*WOWMOM 2008*), June 2008, pp. 1-8.
  - X. Wang and Dmitri Perkins, "Cross-layer Hop-by-hop Congestion Control in Mobile Ad Hoc Networks," *Proceedings of IEEE Wireless Communications and Networking Conference*, March 2008.

- *Distributed Cognitive Radio Networks.* Our research leads to a rate-adaptive probabilistic medium access protocol (RAP-MAC) for opportunistic spectrum management in cognitive radio networks. The proposed RAP-MAC allows multiple cognitive flows to fairly share the available bandwidth without explicit coordination in a distributed fashion. Simulation evaluation shows that RAP-MAC achieves between 65% to 119.5% higher goodput with significantly better fairness characteristics, when compared with existing greedy approaches that overlook the spectrum sensing limitations, as outlined in the following articles:
  - A. Khattab, Dmitri Perkins, and M. A. Bayoumi, "Rate-Adaptive Probabilistic Spectrum Management for Cognitive Radio Networks," *Proceedings of IEEE International Symposium on World of Wireless, Mobile and Multimedia Networks*, June 2011.
  - A. Khattab, Dmitri Perkins, and M. A. Bayoumi, "Probabilistic Framework for Opportunistic Spectrum Management in Cognitive Ad hoc Networks," *EURASIP Journal on Wireless Communications and Networking*, vol. 188, pp. 2011, November 2011.

(3) Grid Computing

- *ResGrid and UCoMS Grid Portal*. The ResGrid toolkit makes use of the Globus toolkit, which encompasses key procedures, such as remote resource allocation (GRAM), high-performance and secure data transfer (GridFTP), to allow users to automatically generate models for simulation-stage in/out data, task farming, and monitoring the status of the jobs. ResGrid was used successfully by our application team to run their applications. The source code of the toolkit is available at the CCT UCoMS CVS server. Meanwhile, we implemented the Grid portal for reservoir uncertainty analyses, based on GridSphere technology, which has become the de facto standard for Grid portals. We have also defined the desired characteristics of a Grid portal for drilling performance analyses. Significant findings and accomplishments are included in:
  - Garbrielle Allen *et al*., "The Grid Application Toolkit: Towards Generic and Easy Application Programming Interfaces for the Grid," *Proceedings of the IEEE*, vol. 93, pp. 534-550, Mar. 2005.
  - Z. Lei, D. Huang, A. Kulshrestha, S. Pena, Gabrielle Allen, X. Li, R. Duff, S. Kalla, Chris D. White, and John R. Smith, "Leveraging Grid Technologies for Reservoir Uncertainty Analysis," *Proceedings of High Performance Computing Symposium* (HPC 2006), April 2006.
  - D. Huang, Gabrielle Allen, C. Dekate, H. Kaiser, Z. Lei, and J. MacLaren, "GetData: A Grid Enabled Data Client for Coastal Modeling," *Proceedings of High Performance Computing Symposium* (HPC 2006), April 2006.
  - Z. Lei, D. Huang, A. Kulshrestha, S. Pena, Gabrielle Allen, X. Li, R. Duff, S. Kalla, Chris D. White, and John R. Smith, "ResGrid: A Grid-aware Toolkit for Reservoir Uncertainty Analysis," *Proceedings of IEEE International Symposium on Cluster Computing and the Grid* (CCGrid 2006), May 2006.
  - S. Pena, D. Huang, X. Li, Z. Lei, Gabrielle Allen, and Chris D. White, "A Generic Task-Farming Framework for Reservoir Analysis in a Grid Environment," *8th Workshop on High Performance Scientific and Engineering Computing* (HPSEC-06), August 2006.
- *Execution Checkpointing in Mobile Grids.* As a Mobile Grid (MoG) is subject to relatively unreliable connections and node mobility at will, it is critical to deal with effective execution checkpointing in MoGs so that they can support productive execution. We have devised heuristic algorithms able to attain highly reliable checkpointing arrangements in a decentralized fashion,

following our Reliability Driven (ReD) protocol for QoS-aware checkpointing. ReD works to maximize the probability of checkpointed data recovery during job execution, increasing the likelihood of a distributed application executed on the MoG to complete without sustaining an unrecoverable failure. Recently, we have addressed intelligent dissemination of checkpointed files in MoGs to ensure practical recovery by exploiting the wireless broadcast medium and random linear network coding. Our considered quiescent intelligent dissemination of checkpointed files is information flow-aware, able to achieve a desired mix of packet transmission and packet reception for best execution recovery. Key research results are covered by articles below:

- P. J. Darby III and Nian-Feng Tzeng, "Peer-to-Peer Checkpointing Arrangement for Mobile Grid Computing Systems," *Proceedings of 16th IEEE International Symposium on High Performance Distributed Computing* (*HPDC 2007*), June 2007.
- P. J. Darby III and Nian-Feng Tzeng, "Decentralized QoS-Aware Checkpointing Arrangement in Mobile Grid Computing," *IEEE Transactions on Mobile Computing*, vol. 9, pp. 1173-1186, August 2010.
- P. J. Darby III and Nian-Feng Tzeng, "Quiescent Intelligent Dissemination of Checkpointed Files for Improved Execution Recovery in Mobile Grids," in preparation for submission.

■ *Peer-to-Peer Resource Discovery*. Based on a distributed hash table (DHT) approach, we have arrived at efficient resource discovery (ReD) for computational Grids, with a unique feature that permits all nodes associated with the same resource type to form a layer so that multiple layered resources are constructed for a given Grid. Resource announcements are disseminated in a controlled fashion among nodes only within the same resource layers, depending upon their stability over time and following the underlying DHT structure. Separately, we have introduced a fast and scalable ReD mechanism, dubbed FaSReD, in support of multi-attribute range queries for resource discovery in heterogeneous Grids. Based on a prefix hash tree (PHT) and built on top of a distributed hash table, FaSReD satisfies multi-attribute range queries by searching over the PHT with low traffic overhead to achieve efficient resource discovery and high scalability. Key research results on this topic are covered by two articles below:

- I. Chang-Yen, D. Smith, and Nian-Feng Tzeng, "Structured Peer-to-Peer Resource Discovery for Computational Grids," submitted for possible presentation in a conference.
- M. M. Ghantous, D. Smith, and Nian-Feng Tzeng, "FaSRed: Fast and Scalable Resource Discovery in Support of Multiple Resource Range Requirements for Computational Grids," *Proceedings of 7th IEEE International Symposium on Network Computing and Applications* (*NCA '08*), July 2008, pp. 45-51.

■ *Energy Consumption Modeling.* We developed a run-time energy consumption model for relating server energy consumption to its overall thermal envelope, by means of hardware performance counters and experimental measurements. Our modeling is different from prior work in that it links system energy input to subsystem energy consumption based on a small set of tightly correlated parameters. The proposed energy model takes into account processor power, bus activities, and system ambient temperature for real-time prediction on the power consumption of long running jobs. It is based on chaotic time series approximation for run-time power consumption, arriving at the Chaotic Attractor Predictor (CAP) with polynomial time complexity while exhibiting high prediction accuracy, as verified by a set of common processor benchmarks. Our CAP is a superior predictive mechanism over existing linear auto-regressive methods, which require expensive and complex corrective steps to address the non-linear and chaotic aspects of the underlying physical system.

- A. Lewis, J. Simon, and Nian-Feng Tzeng, "Chaotic Attractor Prediction of Run-time Energy Consumption Based on Workload in Server Systems," *Proceedings of USENIX 2010 Workshop on Power Aware Computing and Systems* (*HotPower '10*), October 2010
- A. W. Lewis, Nian-Feng Tzeng, and S. Ghosh, "Run-Time Energy Consumption Estimation for Server Workloads Based on Chaotic Time-Series Approximation," accepted in May 2012 for publication in *ACM Transactions on Architecture and Code Optimization* (*TACO*).

■ *Grid Workflow and Dataflow.* We developed Pelecanus for closed-loop applications, with improved job management in reservoir studies. Meanwhile, end-to-end workflows were implemented for the EnKF stochastic inversion package with two numerical reservoir flow simulators, UTChem (publicly available from the University of Texas at Austin) and BlackOil (developed by the UCoMS team and to be released publically). These *concrete* workflows were implemented using Condor-G and DAGMan technologies, which ensure automation and reliability of the end-to-end processing of these applications. *Abstract* to concrete workflow generation was automated using the Pegasus tool. We developed methods to dynamically select the best available computation sites during the concrete workflow generation step. In addition, stage-in and stage-out steps of these workflows were optimized using the Stork scheduler. Different techniques such as data fusion and multiple streams were used for the optimizations. These methods improve transfer speeds and data integrity. Those methods improve transfer speeds and data integrity, under the profiled data access patterns we obtained. Details of these research topics can be found in the following publications:

- Z. Lei, Z. Yun, and G. Allen, "Grid Resource Allocation," Book Chapter to appear in *Grid Computing: Technology, Service, and Application*. CRC Press, LLC (2008), ISBN: 10- 1420067664.
- X. Wang, D. Huang, I. Akturk, M. Balman, G. Allen, and T. Kosar, "Semantic-Enabled Metadata Management in PetaShare," *International Journal of Grid and Utility Computing* (*IJGUC*), 2009.
- T. Kosar and and M. Balman, "A New Paradigm: Data-Aware Scheduling in Grid Computing," *Future Generation computer Systems*, vol. 24, pp. 406-413, April 2009.
- G. Allen, P. Chakraborty, D. Huang, Z. Lei, J. Lewis, C. D. White, X. Xu, and C. Zhang, "Workflow Approach to Designed Reservoir Study," *Proceedings of 2nd Workshop on Workflows in Support of Large-Scale Science* (*WORKS '07*), 2007.
- P. Chakraborty, G. Allen, Z. Lei, J. Lewis, A. Lewis, I. Chang-Yen, I. Jangjaimon, and N. Tzeng, "Integrated Grid Portal for Managing Energy Resources," *Proceedings of 3rd IEEE International Conference on e-Science and Grid Computing*, December 2007, pp. 25-33.
- X. Li, Z. Lei, C. D. White, G. Allen, G. Qin, and F. Tsai, "Grid-Enabled Ensemble Subsurface Modeling," *Proceedings of 19th IASTED International Conference on Parallel and Distributed Computing and Systems* (*PDCS 2007*), November 2007.
- D. Hung, X. Wang, G. Allen, and T. Kosar, "Semantic-Enabled Metadata Framework for Data Grids," *Proceedings of International Workshop on P2P, Parallel, Grid and Internet Computing (3PGIC-2008)*, March 2008.
- E. Yildirim, M. Balman, and T. Kosar, "Dynamically Tuning Level of Parallelism in Wide Area Data Transfer," *Proceedings of International Workshop on Data-Aware Distributed Computing* (*DADC 2008*, in conjunction with HPDC'08), June 2008.

- Z. Lei, Z. Yun, G. Allen, X. Li, and N. Tzeng, "Improving Application Execution in Multicluster Grids," *Proceedings of 11th IEEE International Conference on Computational Science and Engineering*, July 2008.
- Z. Yun, M. Xie, F. Zhou, G. Allen, T. Kosar, and Z. Lei, "Collaborating Mechanical Design Phases across a Grid," *Proceedings of 11th IEEE International Conference on Computational Science and Engineering*, July 2008.
- E. Yildirim, I. Suslu, and T. Kosar, "Which Network Measurement Tool Is Right for You? A Multidimensional Comparison Study," *Proceedings of IEEE/ACM International Conference on Grid Computing* (*Grid 2008*), September 2008.
- I. Suslu, F. Turkmen, M. Balman, and T. Kosar, "Choosing Between Remote I/O Versus Staging in Large Scale Distributed Applications," *Proceedings of ISCA 21st International Conference on Parallel and Distributed Computing and Applications* (*PDCCS 2008*), September 2008.
- M. Balman and T. Kosar, "Dynamic Adaptation of Parallelism Level in Data Transfer Scheduling," *Proceedings of Second International Workshop on Adaptive Systems in Heterogeneous Environments (ASHE 2009)*, March 2009.
- M. Balman and T. Kosar, "Early Error Detection and Classification in Data Transfer Scheduling," *Proceedings of 2009 International Conference on Complex, Intelligent and Software Intensive Systems* (*CISIS '09*), March 2009, pp. 457-462.
- X. Wang and T. Kosar, "Design and Implementation of Metadata System in PetaShare," *Proceedings of 21st International Conference on Scientific and Statistical Database Management* (*SSDBM 2009*), June 2009.
- E. Yildirim, D. Yin, and T. Kosar, "Balancing TCP Buffer vs. Parallel Streams in Application Level Throughput Optimization," *Proceedings of International Workshop on Data-Aware Distributed Computing* (*DADC '09*, in conjunction with HPDC '09), June 2009.
- X. Wang, D. Huang, I. Akturk, M. Balman, G. Allen, and T. Kosar, "Semantic-Enabled Metadata Management in PetaShare," *International Journal of Grid and Utility Computing* (*IJGUC*), vol. 1, no. 4, pp. 275-286, 2009.
- T. Kosar and and M. Balman, "A New Paradigm: Data-Aware Scheduling in Grid Computing," *International Journal of Grid Computing* (*FGCS*), vol. 25, no. 4, pp. 406-413, 2009.
- T. Kosar, M. Balman, I. Suslu, E. Yildirim, and D. Yin, "Data-Aware Distributed Computing with Stork Data Scheduler." *Proceedings of SEE-GRID-SCI'09*, December 2009.
- M. Balman and T. Kosar, "Error Detection and Error Classification: Failure Awareness in Data Transfer Scheduling," *International Journal of Autonomic Computing*, vol. 1, no. 4, pp. 425-446, December 2010.
- E. Yildirim, D. Yin, and T. Kosar, "Prediction of Optimal Parallelism Level in Wide Area Data Transfers," *IEEE Transactions on Parallel and Distributed Systems*, vol. 22, no. 12, pp. 2033-2045, December 2011.

(4) Applications

- *Real-Time Production and Drilling Problems Identification*. A more accurate method was developed for diagnosing the liquid loading problem, to better predict abnormal production declines. As pressure instability is one of the major threats in under-balanced drilling, possibly

causing failures of drilling if not monitored closely and corrected in time. We developed a mathematical model that incorporates pressure data from real time measurements during drilling for pressure instability analyses. Key findings are included in the following journal articles:

- Boyun Guo and A. Ghalambor, "Characterization and Analysis of Pressure Instability in Aerated Liquid Drilling," *Journal of Canadian Petroleum Technology*, vol. 45, July 2006.
- K. Sun, Boyun Guo, and A. Ghalambor, "An Analytical Solution for Aerated Mud and Foam Drilling Hydraulics in Deviated Holes," *Journal of Canadian Petroleum Technology*, vol. 45, Mar. 2006.

- *Reservoir Simulation Improvement.* We have addressed reservoir simulation performance by (1) distributing actual Kalman gain computation for better memory utilization and decreased data transmission requirements, (2) adopting better data transmission formats, made possible by implementing HDF5 in Cactus BlackOil, and (3) devising methods to select small but robust prior ensembles, based on fast screening simulations and singular value decompositions. Research outcomes were reported in the following articles:
  - Z. Lei, G. Allen, P. Chakraborty, D. Huang, J. Lewis, X. Li, and C. D. White, "Grid-Enabled Problem Solving Environment for Advanced Reservoir Uncertainty Analysis," *Concurrency and Computation: Practice and Experience*, vol. 20, June 2008, pp. 2123-2140.
  - S. Kalla, C. D. White *et al*., "Imposing Multiple Seismic Inversion Constraints on Reservoir Simulation Models Using Block and Sequential Methods," submitted under review for possible publication in *SPE Journal*.
  - S. Kalla, C. D. White *et al.*, "Stratigraphic Stacking Patterns in Downscaling Seismic Data to Fine-Scale Flow Models," *Proceedings of 2009 AAPG Annual Convention and Exhibition*, June 2009.
  - E. Ceyhan, G. Allen, C. D. White, and T. Kosar, "A Grid-Enabled Workflow System for Reservoir Uncertainty Analysis," *Proceedings of 6th ACM/IEEE International Workshop on Challenges of Large Applications in Distributed Environments* (*CLADE 2008*, in conjunction with HPDC'08), June 2008, pp. 45-52.
  - X. Li, C. D. White, Z. Lei, and G. Allen, "Reservoir Model Updating by Ensemble Kalman Filter- Practical Approaches Using Grid Computing Technology," *Proceedings of EAGE Conference on Petroleum Geostatistics*, June 2007.
  - X. Li, C. D. White, Z. Lei, and G. Allen, "Beyond Queues: Using Grid Computing for Simulation Studies," *Proceedings of SPE Digital Energy Conference and Exhibition*, April 2007.
  - X. Li, C. D. White, Z. Lei, and G. Allen, "Using Designed Reservoir Simulations and Grid Computing to Compare Geostatistical Simulation Algorithms," *Proceedings of Fifth Institute for Mathematics and its Applications conference on Modeling Permeable Rocks*, April 2007.
  - B. Guo and X. Wang, "Testing of New High-Order Finite Difference Methods for Solving Convection-Diffusion Equation," *E-Journal of Reservoir Engineering*, Oct. 1005.
- *Multilateral and Horizontal Wells.* A more accurate method, which allows different IPRs of laterals and permits cross-flow among laterals, has been developed for predicting composite IPR of multilateral wells. By combining the composite IPR model with Poettmann & Carpenter correlation, a computer simulator has been developed for predicting the well production rate, with oil and gas wells treated differently. A case study with the measured production rate indicated that our simulator gave rise to accuracy within 3.1%. Additionally, we devised an analytic model

for inflow performance prediction of horizontal wells. Results and findings of our well investigation can be found at:

- Boyun Guo, K. Lin, and A. Ghalambor, "A Rigorous Composite-IPR Model for Multilateral Wells," *Proceedings of SPE Annual Technical Conference and Exhibition* (*ATCE 2006*), Paper No. SPE 100923, Sept. 2006.
- Boyun Guo, J. Zhou, Y. Liu, and A. Ghalambor, "A Rigorous Analytical Model for Fluid Flow in Drain Holes of Finite Conductivity Applied to Horizontal and Multilateral Wells," *Proceedings of SPE 2007 Production Operations Symposium*, Paper No. SPE 106947, April 2007.
- Boyun Guo, J. Zhou, and A. Ghalambor, "Effects of Friction in Drain Hole on Productivity of Horizontal and Multilateral Wells," Paper No. SPE 106948, *Proceedings of SPE 2007 Asia Pacific Oil and Gas Conference & Exhibition* (*APOGCE*), Oct./Nov. 2007.
- Q. Fang, Boyun Guo, and A. Ghalambor, "Formation of Underwater Cuttings Piles in Offshore Drilling," *Journal of SPE Drilling & Completion*, vol. 23, no. 1, pp. 23-28, March 2008.
- Boyun Guo, C. Ai, and L. Zhang, "A Simple Analytical Model for Predicting Gas Productivity of Horizontal Drain Holes with High-Friction," Paper No. SPE 108390, *Proceedings of SPE Western Regional Meeting*, Mar./Apr. 2008.
- Boyun Guo, J. Zhou, K. Ling, and A. Ghalambor, "A Rigorous Composite-IPR Model for Multilateral Wells," *Journal of SPE Production & Operations*, vol. 23, no. 2, pp. 241-248, May 2008.
- Boyun Guo and X. Yu, "A Simple and Accurate Mathematical Model for Predicting Productivity of Multifractured Horizontal Wells," Paper No. SPE 114452, *Proceedings of CIPC/SPE Gas Technology Symposium 2008 Joint Conference*, June 2008.
- X. Yu, Boyun Guo, and Z. Bu, "A Comparison between Multi-Fractured Horizontal and Fishbone Wells for Development of Low-Permeability Fields," Paper No. SPE 120579, *Proceedings of the SPE Asia Pacific Oil and Gas Conference and Exhibition*, August 2009.
- Boyun Guo and X. Yu, and M. Khoshgahdam, "A Simple and Accurate Mathematical Model for Predicting Productivity of Multifractured Horizontal Wells," *SPE Reservoir Evaluation & Engineering Journal*, vol. 12, no. 6, December 2009.
- Boyun Guo, "Corrections to Horizontal Drainhole Productivity Equations for Wellbore Friction Effect," *Journal of Petroleum Science and Engineering*, vol. 70, January 2010, pp. 344-349.

■ *Real-Time Model Inversion and Optimization.* We have implemented the simulators and the ensemble Kalman filter within a high-performance, scalable parallel framework (PETSc). This allows treatment of large ensembles with many members each with 10^6 or more gridblocks. This has been demonstrated using hundreds of simulation models distributed across more than 10^4 processors on several different clusters, simultaneously. The parallel implementation includes current best practices including inflation, localization, and treatment of non-Gaussian error distributions. Our simulation frameworks for managing data communication involve PetaShare to let the underlying infrastructure manage the low-level data handling issues and SAGA (Simple API for Grid Applications) for large-scale and distributed computation through the BigJob technique. Our work flow integration utilizes files as flags to signal when new data are available for diverse processes, including arrival

picking, ray tracing, simulation, and assimilation via the ensemble Kalman filter (EnKF). Results of this research topic are reported in the following papers:

- M. Tyagi, C, D. White, Y. Feng, and T. Plaksina, "Natural Convection due to the Fluid Circulation in the Energy Extraction from the Sub-Surface in Geopressured Brine Reservoirs," *Proceedings of Third International Conference on Porous Media and its Applications in Science, Engineering and Industry*, June 2010.
- D. Yin, E. Yildirim, and T. Kosar, "A Data Throughput Prediction and Optimization Service for Widely Distributed Many-Task Computing," *Proceedings of Workshop on Many-Task Computing on Grids and Supercomputers* (*MTAGS,* in conjunction with Supercomputing '09), November 2009.
- Y. Y. El Khamra, S. Jha, and C. White, "Modeling Data-driven CO_2 Sequestration Using Distributed HPC Cyberinfrastructure," *Phil. Trans of the Royal Society A*, 2010.
- Y. Feng, M. Tyagi, M., and C. D. White, "Effect of Natural Convection Patterns of Optimal Locations and Size of a Heat Sink in a Geothermal Reservoir," *Proceedings of Thirty-Sixth Workshop on Geothermal Reservoir Engineering*, January/February 2011.
- T. Plaksina, C. D. White, J. Nunn, and T. Gray, "Effects of Coupled Convection and CO_2 Injection in Stimulation of Geopressured Geothermal Reservoirs," *Proceedings of Thirty-Sixth Workshop on Geothermal Reservoir Engineering*, January/February 2011.
- Y. Shuai, C. D. White, H. Zhang, and T. Sun, "Using Multiscale Regularization to Obtain Realistic Optimal Control Strategies," *Proceedings of SPE Reservoir Simulation Symposium*, SPE No. 142043-MS, February 2011.
- Y. Shuai and C. D. White, "Ensemble Kalman Filter with Adaptive Updating, and Application to a Meter–Scale Physical Model," *Proceedings of Sixth International EnKF Workshop*, June 2011.

- *Physical Experiment, Flow Modeling, and Seismic Data Processing.* The previously prototyped instrumentation is fully functional and installed on the sand tank experiment, with its amplifiers overhauled to be more reliable in the moderately damp experimental setting. The pump and five pressure-temperature sensors have been calibrated. All data are now automatically acquired (LabView for seismic, DAQView for rate, pressure and temperature). The data are transported to PetaShare for analysis, with full data sets for testing data integration and model inversion. Our experiments have demonstrated adequate sensitivity to image the air-water interface, and discovered anomalous saturation-velocity behavior (Smolkin et al., 2010; Smolkin, 2011). In addition, a custom-built parallel reservoir simulator is used for flow modeling (El Khamra, 2009). We continue to add features to this simulator (Feng et al., 2011; Plaksina et al., 2011) and to optimize its performance for flow modeling the sand tank. Efficiency is critical when performing inversion, and three major changes have been made to achieve the goal of completing one inversion within three minutes, via optimized parallel configuration to exploit shared memory on multicore processors. Meanwhile, we have conducted integration of seismic data, which requires significantly high data processing due to the need of data acquisition and stacking to improve the signal-to-noise ratio. The stacked data are analyzed to pick the first refraction arrival, and our processing makes use of publicly available input-output and processing routines in Seismic Unix (URL - http://www.cwp.mines.edu/cwpcodes/index.html). Results of this set of accomplishments can be found in the articles below:

  - D. Smolkin, J. Lorenzon, C. D. White, T. Kosar, M. Tyagi, and G. Allen, "Seismic Physical Reservoir Modeling Experiment in a Large Sand-Tank Facility," delivered at the Society of Exploration Geophysicists Fall Meeting, Oct. 2010.

- Y. Feng, M. Tyagi, and C. D. White, "Effect of Natural Convection Patterns of Optimal Locations and Size of a Heat Sink in a Geothermal Reservoir," *Proceedings of Thirty-Sixth Workshop on Geothermal Reservoir Engineering*, January 31 – February 2, 2011.
- T. Plaksina, C. D. White, J. Nunn, and T. Gray, "Effects of Coupled Convection and CO2 Injection in Stimulation of Geopressured Geothermal Reservoirs," *Proceedings of Thirty-Sixth Workshop on Geothermal Reservoir Engineering*, no. SGP-TR-191, January 31 – February 2 2011.
- Y. Shuai and C. D. White, "Ensemble Kalman Filter with Adaptive Updating, and Application to a Meter–scale Physical Model," *Proceedings of Sixth International EnKF Workshop*, 2011.
- Y. Shuai, C. D. White, H. Zhang, and T. Sun, "Using Multiscale Regularization to Obtain Realistic Optimal Control Strategies," *Proceedings of SPE Reservoir Simulation Symposium*, SPE No. 142043-MS, February 2011.
- D. E. Smolkin, J. M. Lorenzo, C. D. White, T. Kosar, M. Tyagi, and G. Allen, "Seismic Physical Reservoir Modeling Experiment in a Sand-Tank Facility," *Eos Trans. AGU, Spring Meet. Suppl.*, Abstract NS- 853347, August 2010.

Major Related Funding

(1) CAREER: Integrated Multi-hop Wireless Networks – PI: Hongyi Wu, funded by NSF CNS, $476,000, July 1, 2004 to June 30, 2012.

(2) CAREER: Designing Large-Scale Ad Hoc Networking Systems: Models, Analysis, and Protocols – PI: Dmitri Perkins, funded by NSF CNS, $479,235, September 1, 2005 to December 31, 2012.

(3) CAREER: Data-aware Distributed Computing for Enabling Large-scale Collaborative Science – PI: Tevfik Kosar, funded by NSF CNS, $400,000, February 15, 2009 to February 14, 2014.

(4) SHF: Small: Reliability Enhancement via Adaptive Checkpointing in Wireless Grids – PI: Nian-Feng Tzeng, funded by NSF Division of Computing and Communication Foundations, $420,000, August 2009 to July 2013.

(5) STCI: Development of Stork Data Scheduler for Mitigating the Data Bottleneck in Petascale Distributed Computing Systems – PI: Tevfik Kosar, funded by NSF Office of Cyber Infrastructure, $495,514, September 2009 to August 2012.

(6) Strategies for Remote Visualization on a Dynamically Configurable Testbed – PI: Gabrielle Allen, funded by NSF Office of Cyber Infrastructure, $299,447, Sept. 15, 2009 to Sept. 14, 2012.

(7) Collaborative Research: Community Infrastructure for General Relativistic MHD (CIGR) – PIs: Tevfik Kosar and Gabrielle Allen, funded by NSF Physics Division, $400,000, October 2009 to September 2012.

(8) NEDG: Featherlight Information Network with Delay-Endurable RFID Support (FINDERS) – PIs: Hongyi Wu and Nian-Feng Tzeng, funded by NSF CNS Core Research, $366,000, September 2008 to August 2013.

(9) MRI: Acquisition of a Wireless Nanonetworks Integration and Emulation System for Multi-Processor SoC Research and Education – Co-PIs: Magdy Bayoumi and Hongyi Wu, funded by NSF CNS, $500,000, August 2008 to July 2011.

(10) MRI: Development of PetaShare: A Distributed Data Archival, Analysis and Visualization System for Data Intensive Collaborative Research, PIs: Tevfik Kosar, Edward Seidel, and Gabrielle Allen, funded by NSF EPSCoR program, $957,678, August 2006 to July 2011.

(11) ALPACA: Cactus Tools for Application Level Performance and Correctness Analysis – Co-Investigators: Gabrielle Allen and M. Tyagi, funded by NSF OCI under the Software Development for Cyberinfrastructure (SDCI) solicitation, $587,070, October 2007 to August 2010.

(12) Center of Excellence in Integrated Smart Sensor Surveillance System – Co-Investigator: Gabrielle Allen, funded by: Louisiana BOR PKSFI, $1,555,521 (LSU), June 2007 to June 2012.

(13) Real-Time Integration of Diverse Data for Surveillance, History Matching, and Optimization – PIs: C. White and J. Lorenzo, funded by Shell E&P Technology Co., $300,000, 2010 – 2013.

(14) High-Rate Flow in Gravel Packed Wells: Completion Characterization and Pressure Transient Behavior – PIs: C. White, M. Tyagi, and others, funded by Shell E&P Technology Co., $300,000, 2010 – 2013.

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Number of Graduate Students supported by DOE: **53**

- *Supported fully* – Suresh Reddy Chintakuntla, Chong Wang, Yan He, J. Zhou, Xin Li, Emir Bahsi, Ashwin Bommathanahalli, Emrah Ceyhan, Ibrahim Suslu, Zhifeng Yun, Leon White, David Smolkin, Mohammad Kazemi, Chih Hsun Chou, Chandra Gurram, Tan Pham, Xiyue Xiang, Xidu Qiu, Su Xia, Hongyu Zhou, Yin Feng, and Ting Sun.
- *Supported partially* – Sherine Abdelhak, Miland Ghantous, Lei Pan, Haining Chen, Rajesh Prasad, Ikhlas Ajbar, Manh Nguyen, Denvil Smith, Boisy G. Pitre, Chris Chaudoir, Seyed Aghdam, Ian Chang-Yen, M. Balman, Adam Lewis, Itthichok Jangjaimon, Mayssa al-Najjar, Ahmed Abdelgawad, Esmaeil Amini, Zahra Jeddi, Randa Ayoubi, Abhijit Sil, Azeez Sanusi, Salim Farah, Tarek Elarabi, Abdelhamid Moursy, Jullawadee Maneesilp, Mohammad Seyed Jalali, and X. Wang.
- *Matching Funds* – Yin Feng, J. Hicks, and Y. Shuai.

Number of Undergraduate Students supported by DOE and by NSF REU: **10**

- *Supported fully* by DOE – John Shu, Henry Watson, Aaron Chauvin, D'Andre Grimes, John Shu, and Henry Watson.
- *Supported partially* by DOE – Rashaad Jackson.
- *Supported partially by NSF REU* – James Scarborough, Ricardo Colas, and Anthony Mai.

Number of Postdoctoral Fellows and Research Scientists supported by DOE: **5**

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