An Overview of the University of Texas at Dallas' Center for Advanced Telecommunications Systems and Services (CATSS)

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The University of Texas at Dallas' Center for Advanced Telecommunications Systems and Services (CATSS) was founded in January 1998 to satisfy the acute needs of the growing Dallas/Richardson telecommunications industry. Its mission is to foster a strong Industry-University partnership to advance local telecommunications industries to the next generation of systems and products. Composed of UTD faculty and industry researchers and managers, the Center's focus is exclusively telecommunications-related fields of study and research. The technical foci of the Center reflect the current needs of the telecommunications industry, including but not limited to wireless and optical networking. The Center's work spans the entire range of available technical expertise—hardware, communications, transmission modalities, algorithms, systems architecture, and applications. As part of its activities, the Center organizes workshops and conferences on topics solicited by industry and the community. It offers seminars and courses featuring talks from leading experts both from the public and private sectors, and publishes journals and magazines. By accomplishing this, CATSS serves as a clearing house for advanced telecommunications research and development in the short run, and incubates long term vision, enabling a continuation of the robust development and rapid expansion of the telecommunications industry.

A Telecommunication Center in the Heart of the Telecom Corridor

In North Texas, where once was open prairie, home to longhorn cattle and cowboys, now stands the Telecom Corridor. The result of over 25 years' growth, the Corridor is home to well-known corporations such as Texas Instruments, Raytheon, Ericsson, Nortel, Alcatel, Worldcom (MCI), Fujitsu, Nokia, Hewlett-Packard, and over 200 other companies.

In the midst of Telecom Corridor sits the University of Texas at Dallas (UTD). Founded by Erik Jonsson and other business leaders from Texas Instruments in 1961, UTD is the leading local supplier of personnel with advanced degrees for the Telecom Corridor. UTD's Erik Jonsson School serves the companies of the Telecom Corridor with a strong program in Electrical Engineering (EE) and Computer Science (CS), and was the first school in the nation to offer a Telecommunications Engineering (TE) degree at both the Master and Bachelor levels.

One of the anchors of the EE/CS/TE programs is the Center for Advanced Telecommunications Systems and Services (CATSS). Founded in 1998 at UTD, CATSS was created to satisfy the acute needs of the growing Dallas/Richardson telecommunications industry.

The Center is a body composed of UTD faculty and industry researchers and managers, tending to exclusively telecommunications-related fields of study and research. The technical foci of the Center reflects the current needs of the telecommunications industry, including but not limited to wireless and optical networking. The Center's work spans the entire range of available technical expertise—hardware, communications, transmission modalities, protocols, systems architecture and applications. As part of its activities, the Center organizes workshops and conferences on topics solicited by industry and the community. It offers seminars and courses featuring specific talks from leading experts both from the public and private sector, and publishes journals and magazines.

The mission of CATSS is to foster a strong industry-university partnership to advance local telecommunications industries to the next generation of systems and products. CATSS thus serves as a clearinghouse for advanced telecommunications research and development in the short run, and directs long term vision for the industry, enabling a continuation of the robust development and rapid expansion of the telecommunications industry.

Telecommunication Challenges

The growth of the Internet, doubling every 100 days (William E. Kennard, Federal Communications Com-mission (FCC) chairman, January 27, 2000 speech in Lisbon, Portugal), demonstrates the exponentially growing demand for telecommunications facilities. While individuals were at one time comfortable accessing Web information over 14.4 kbps and 28.8 kbps modems, more and more users are upgrading to broadband access using xDSL and cable modem. This means that users who once expected only a small, slow flow from the Internet now demand much increased data rates as well as reduced delays. New bandwidth-intensive applications such as video, voice, multimedia, and interactive gaming are driving the push toward higher capacity network backbones.

Wireless access to the Internet is presently at the same point that wired networks were when the Internet started to become popular. Cellular and PCS networks provide connectivity at 9.6 to 19.2 kbps. Standards being readied for near-term commercial deployment will increase access speeds—from 64 kbps on the low end to 144 kbps on the high end—using technologies such as IS-95B, GPRS (General Packet Radio Service) and EDGE (Enhanced Data rates for GSM). Third generation (3G) systems currently in design will provide 384 kbps to mobile subscribers and as much as 2 Mbps for Wireless Office networks.

Network infrastructures are changing rapidly, too. WDM (Wavelength Division Multiplexing), carrying numerous simultaneous SONET/SDH links, is multiplying the capacity of a single fiber optic strand toward its multi-terabit per second capacity, greatly exceeding the limits imposed by the 10 Gbps capacity of a SONET OC-192. ATM over SONET is being replaced by Packet Over SONET, while standards development presently underway is working out the details that will enable Packet over WDM (also called "IP over glass").

It is within this dynamic environment that CATSS personnel are pursuing their research. The emphases within CATSS are aligned with the developing needs of the market place, emphasizing both the wireless and hard-wired infrastructure needs of the telecommunications industry.

CATSS Areas of Research

Out of the multiple areas of focus CATSS researchers have been engaged in, we highlight here some of the concrete research thrusts in the area of wireless and mobile networking, with a brief mention of optical research, for the sake of completeness. Due to space limitations, instead of citing individual references interested readers are referred to the CATSS web site for more details on relevant publications.

Ad Hoc Networking

The goal of this part of research is to define and devise novel system architectures, technologies, and algorithms for networks in which all the nodes can be mobile (also called multihop wireless networks, or more often, *ad hoc networks*). Ad hoc networks, initially mainly confined in the military tactical domain, are recently gaining commercial importance given the increasing deployments of devices based on standards such as IEEE 802.11 and Bluetooth. Ad hoc networking concerns now a wide variety of networks architectures, which are used to implement a flourishing variety of corresponding applications. From the "classic" military network, with up to few hundreds of nodes, ad hoc networking is now the technology used for implementing *sensor networks*, i.e., networks made up of potentially tens of thousands of very small sensing devices.

A selection of the projects currently under investigation, several of which are supported by funding from the U.S. Department of Defense (DoD), NSF and companies of the Telecom Corridor are described below.

A Reliable Available High Performance Integrated Multimedia Delivery (RAPID) Network

This project deals with providing network support for the future battlefield that will have to handle large networks with many mobile nodes which have to quickly connect and reconnect with a rapidly varying set of radio neighbors. To support the Army's needs in this scenario, targeting high mobility and multimedia communications support, with emphasis on reliability and survivability, we propose a novel architecture called Reliable, Available, high Performance Integrated multimedia Delivery (RAPID), for network support of multimedia communications in large, highly mobile networks.

Our basic design principle for multimedia support in a mobile environment is the vertical integration of a robust control channel access and an efficient virtual cellular network, which are combined into a reliable communication system satisfying the above requirements. The reliability and the robustness of the (signaling) control channel are utilized to construct a highly available mobile cellular system with virtual base stations, which, on request, can allocate bandwidth to mobile users. This type of bandwidth allocation to applications in a mobile system can uniquely support highly available and efficient voice, video and image transmission at full channel capacity in the tactical environment. The separation of the bandwidth between a signaling channel for control and a (wider bandwidth) channel for use in the cellular network to support multimedia applications can be accomplished in the frequency or code domains. In addition, the control channel can be used for data delivery, in support of reliable connectionless, datagram communication, without the need to incur the overhead of call setup and bandwidth allocation by base stations. RAPID uses the guaranteed data signaling channel to construct and continuously update a Virtual Cellular Network Structure. This is obtained by clustering the mobile nodes into virtual cells controlled by "mobile base stations." The mobile nodes communicate with the base stations to establish a connection and exchange the necessary control information. The Virtual Cellular Network is pro-actively self-organizing. The formation and reorganization of virtual cells takes place continuously and autonomously in the background utilizing the control channel, rather than in an event-driven fashion. All mobile nodes are allowed to compete for the role of a base station. Base stations are connected into a Virtual Backbone Network, realized either via direct satellite links or by multiple routes through the radio network itself. The Virtual Backbone Network is continuously maintained in the changing topology, to maximize its availability as a reliable highway system. Beyond maintaining connectivity, the existence of a backbone network makes it possible to provide Quality of Service (QoS) support via bandwidth provisioning, including possible support for prioritized and mission critical traffic.

CATSS in the GloMo Community: the TSMA concept

The Global Mobile (GloMo) Information Systems is one of the leading projects funded by DARPA since the early Nineties. The mission of this project, which involves over thirty among academic institutions and companies, is to make the mobile environment a first-class citizen in the Defense Information Infrastructure, and to provide user friendly connectivity and access to services for wireless mobile users (see also http://www.darpa.mil/ito/research/glomo/).

The objective of our research in the GloMo project, conducted in cooperation with BBN, is to develop and test a new control/signaling mechanism for ad hoc tactical networks. This mechanism is targeted to solve the fundamental signaling problems in these networks where current access mechanisms are inherently unsatisfactory for implementing a fail-safe control/signaling channel. The proposed mechanism provides an ideal, scalable and fail-safe, guaranteed delivery solution for carrying control information in support of error-recovery, reliability and survivability.

The control channel mechanism is based on the new Time Spread Multiple Access (TSMA) protocol. The TSMA protocol used for the realization of the control channel solves the problems inherent in existing access protocols that serve as a basis for signaling channels today. Its unique properties include:

- Guaranteed channel access to each node within a deterministically bounded access delay (as opposed to probabilistic protocols such as Aloha).
- No requirement for re-assignment of time slots as the topology changes (contrary to spatial reuse TDMA).
- Deterministic access delay bound which grows only logarithmically with the network size (compared to linear growth for TDMA).
- The possibility of incorporating feedback information (acknowledgments) within the protocol itself, thus making the protocol its own control/feedback channel.

These properties make TSMA an ideal basis for the implementation of a reliable control/signaling channel with a guaranteed quality of service control channel and a potential contender for a data access protocol with these properties.

CATSS and the IETF MANET Working Group: GPS-enabled Ad Hoc Routing and Multicast

The Internet Engineering Task Force has created a working group for the development of Mobile Ad hoc NETworks (MANETs) routing and multicast specifications and their introduction to the Internet Standards track. Following the working group guidelines, CATSS members have proposed several routing and multicast protocols for MANETs.

Our approach to routing is based on the observation that in an ad hoc network, i.e., in a completely mobile scenario, the conventional way to represent route information (as next-hop neighbors, or as a list of neighboring nodes) is no longer as effective as in wired or wireless cellular networks, where a fixed infrastructure can be used as a stable "route reference system." Exchanging routing tables among nodes in the ad hoc setting would generate unbearable overhead. Our idea is to exploit a predefined, stable and reliable positioning system, based on which each node can be constantly aware of its own location and the location of other nodes in the network. In order to achieve this goal, we proposed to use positioning system devices, such as the widely commercially available Global Positioning System (GPS) receivers. The total concept of using GPS in ad hoc networks, and its possible application to wireless communications in general, is of interest to CATSS researchers.

In our approach, the routing table stored at each node contains *location information* for any other node in the network (e.g., geographic coordinates that can be obtained by the use of GPS). When a node A wants to send a message m to a node B, it uses the location information for B to obtain B's *direction*, and then transmits m to all its one hop neighbors in the direction of B. Each neighbor repeats the same procedure, until B, if possible, is eventually reached.

The probability of finding B in the computed direction relies on how the location information is disseminated through the network. In our model, each node transmits control messages bearing its current location to all the other nodes. The frequency with which these control messages are transmitted is determined by:

The *distance effect*: The greater the distance separating two nodes, the slower they appear to be moving with respect to each other. Thus, nodes that are far apart, need to update each others locations less frequently than nodes closer together. This is realized by associating with each control message an "age" which corresponds to how far from the sender that message travels.

The *mobility rate*: The faster a node moves, the more often it must communicate its location. This allows each node to self optimize its dissemination frequency, thus transmitting location information only when needed and without sacrificing the route accuracy.

Since distance and mobility play a central role in our protocol, we name it the *Distance Routing Effect Algorithm for Mobility* (DREAM) protocol for ad hoc networks. DREAM achieves the following desirable properties: It is *bandwidth and energy efficient* (each control message carries only the coordinates and the identifier of a node); it is *robust* (the data message can reach its intended destination by following possibly independent routes), and t is *adaptive to mobility*, (the frequency with which the location information is disseminated depends on the mobility rate).

PCS networking

In the realm of wireless *cellular* networks, i.e., those networks that rely on a fixed infrastructure of *base stations*, CATSS researcher have explored two main directions:

- We introduced large number of analytical models for the study of channel occupancy times and handoff rate for networks organized in cells and carrying multimedia type traffic, which are unique in being designed under the realistic operational assumption of non-exponential distributions of traffic in PCS systems. Analytical formulae for computing channel occupancy times and handoff rates under a general mobility assumption were obtained for the first time. It was shown that these results are generally applicable to any network organized in a cellular structure, such as the more general Personal Communication System (PCS) networks or other future multimedia networks.

- One of the key problems within any cellular type system is mobility management. In existing cellular systems, mobility management generally entails passive network involvement in keeping track of user locations and in maintaining connections. No per user resources are pre-allocated and the probability of blocking is high as the mobile user moves between cells. We proposed a novel method which facilitates efficient mobility management through user trajectory prediction in situations which have previously been thought to be unpredictable. Our approach is based on viewing the trajectory prediction problem as a stochastic estimation and filtering problem, extracting the necessary mobility information from practically available measurements such as the RF signal strength. Thus, trajectory estimation is obtained from real-time observations and a high degree of prediction accuracy is guaranteed even when the system has no prior information about the user's mobility history. This method is further combined with the pattern matching methods to achieve robust next-cell prediction and the prediction of the subsequent cell sequence the user is expected to cross. To achieve this, we propose an optimum filter, implemented as an extended, self-learning Kalman filter. With good next-cell prediction, algorithms that improve hand-offs, relieve congestion, provide advance resource reservations, provide advance optimal route establishment, and which improve the overall QoS in wireless networks are obtained.

Mobile IP

Mobile IP describes the emerging integration of wireless communications with the data communications infrastructure. Supporting mobility in an IP environment requires new, or at least significantly modified, location and security procedures, link layer protocols, routing protocols, platform support, etc.

Work being performed in CATSS looks at the evolving standards, and is focused on creating a simulation tool for Mobile IP networks in order to evaluate performance under varying network and mobility conditions. The component modules of the simulator provide the functionality required to support mobile data terminals. The first module, foundational to Mobile IP, is mobility management, based on knowing a terminal's location and radio frequency (RF) related issues such as channel, interference, signal strength, etc. A second module allows the study of link layer protocols that manage the point-to-point data transfer between a pair of nodes connected by a wireless rather than a wired link. Dynamically determining the routing necessary to deliver a packet to a user whose location is (initially) uncertain, or which may vary during the delivery of a packet stream is provided by a third module. End-to-end reliability is provided by a module that takes mobility into account within the defined realm of transport protocols. Other modules include an advanced traffic generator that enables simulation of traffic in the presence of other traffic sources, a topology generator, and a network cloud simulator.

To complete the package, a statistical analysis toolkit to define the simulations and then analyze the resulting data, a debugging tool, and a graphical user interface are also under study.

Optical Networking at CATSS

CATSS members are involved in research that concerns several different aspects of the rapidly evolving field of optical communications. Among other topics CATSS member have proposed innovative results in the areas of network protection and fault-tolerance, bandwidth allocation and network design and optimization. As the orientation of this publication is wireless and mobile networking, in the rest of this section we only briefly describe on-going projects in this area.

Lightpath establishment and protection in optical networks. Emerging all-optical networks are expected to rely on optical cross-connects, enabling data to be routed through the network entirely in the optical domain. Configuring these optical devices across a network will enable one to establish all-optical connections, or *lightpaths*, between a source node and a destination node. The establishment of lightpaths requires the development of control and management protocols for performing various functions such as selecting a route for the connection, selecting a wavelength for the connection, reserving network resources, and configuring the optical cross-connects. The control and management functions may also include protection and restoration capabilities.

Bandwidth on Demand. Bandwidth on demand (BoD) means that, instead of having the capacity be explicitly set aside at the construction of the network, WDM network capacity is allocated to a user or an application dynamically. The methods used to make the capacity available can be anything from pulling new fibers, to plugging in new interface cards in the network nodes, to 'point and click provisioning,' (based on the 'point and click' in a GUI of a network management web site, which is the most popular case in the 'next generation MAN/WAN' being developed), and even to fully automated centralized/distributed allocation methods. The delay between request and allocation may vary from months to nanoseconds. Among these, we focus our research efforts on distributed high-speed (sub-millisecond scale) bandwidth on demand in metropolitan area networks.

Use of Computational Intelligence Techniques for Designing Optical Networks. In this part of CATSS research we show that heuristic techniques, often applied in Computational Intelligence (CI), Artificial Intelligence, and Operational Research optimization problems, can be used in optical networks to provide near-optimal and fast solutions for efficient network design and management.

CATSS Publications and Activities

The Center has contributed significantly to the telecommunications research community, developing leading edge analytical tools and innovative solutions in such areas as wireless and mobile computing, high-speed networks, and optical communications. Its contributions have been presented at leading international conferences and major workshops (e.g., GLOBECOM, ICC, INFOCOM, MOBICOM, etc.), and have been published in the most prestigious technical journals (e.g., Transactions on Networking, JSAC, Wireless Networks, MONET, etc.). CATSS personnel have contributed significantly to a new book on PCS networks, "Mobile and Wireless Network

Protocols and Services," being published by John Wiley & Sons. The CATSS director is the Editor in Chief of leading journals on wireless communications and applications such as ACM/Baltzer Wireless Networks and ACM/Baltzer Journal on Special Topics in Mobile Networking and Applications (MONET). Recently, CATSS, along with the SPIE and Baltzer Science Publishers, was behind the creation of the Optical Networks Magazine (http://www.optical-networks.com), which covers technologies, architectures, services, and applications in the fields of optical telecommunications and networking systems. CATSS sponsored workshops and conferences such as MobiCom'98 that was held in Dallas in October 1998. In January 2000 the Workshop on Optical Networks, ONW2000, was held at UTD. This workshop focused on approaches and solutions for realizing optical networks in long haul, metropolitan, and local-access environments. (Proceedings from this conference may be obtained from http://catss.utdallas.edu/ONW2000.) Planned for October 2000 is the first Optical Networks and Communications Conference, OptiCom2000. (Information about this conference may be found at http://www.opticomm.org.) Supported by SPIE, IEEE, and ACM, OptiCom plans to become a major venue for sharing the latest results and developments in this area.

CATSS Future Growth and Goals

CATSS is poised to parallel and support the continued growth of the Richardson Telecom Corridor, by acting as liaison between UTD CATSS academia and local industry. CATSS platform is to conduct advanced research in wireless, focusing on PCS and ad hoc networks, and infrastructure that emphasize fiber-based networks. This approach will be accomplished through the following steps.

CATSS will pursue the responsibility to develop significant information exchange for current and future engineers. CATSS will endorse scientific-personnel exchange and engineer re-training programs.

CATSS will foster summer internships for graduates and undergraduates to meet future needs of local industry. Additional outreach programs will be implemented at the secondary (high school) level with the intent to attract and identify engineers at an earlier age.

Lastly, CATSS will augment its on-going cooperation with telecommunication companies. The *Charter Company Membership* in CATSS entitles the contributing companies to several benefits, which, together with research partnership, include faculty alliance, ensuring faculty commitment and resources toward projects of participating companies, and professional development, through which Charter Members will be involved in the organization of conferences, tutorial, journal special issues, distinguished lectures, and other similar activities.

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Biographies

Imrich Chlamtac holds a Ph.D. degree in computer science from the University of Minnesota, and B.Sc. and M.Sc. degrees awarded with the Highest Distinction from Tel Aviv University. Since 1997 he holds the Distinguished Chair in Telecommunications at the University of Texas at Dallas, where he is also the Director of CATSS, the Center for Advanced Telecommunications Systems and Services. Prior to joining UTD, Dr. Chlamtac was on faculty at Technion—The Israel Institute of Technology—and the University of Massachusetts in Amherst. Dr. Chlamtac is also the recipient of the titles of Senior Professor at Tel Aviv University, and of University Professor at the Technical University of Budapest. Dr. Chlamtac is a Fellow of the IEEE and ACM societies for numerous contributions to networking, including the concept of lightpath or wavelength routing and contention free channel access methods. Dr. Chlamtac published over two hundred and fifty papers in refereed journals and conferences and is the co-author of the first textbook on Local Area Networks and on Mobile and Wireless Networks Protocols and Services (John Wiley & Sons, Pub.). Dr. Chlamtac serves as the founding Editor in Chief of the ACM/URSI/Baltzer Wireless Networks, Mobile Networks and Applications (MONET) journals, and the SPIE/Baltzer Optical Networks Magazine (ONM) and has served on the editorial boards of most major publications in telecommunications. Dr. Chlamtac is the founder of ACM/IEEE MobiCom and SPIE/IEEE/ACM OptiCom conferences.

Stephen Gibbs serves in the capacity of Visiting Senior Lecturer at the University of Texas at Dallas, where he teaches undergraduate telecommunications classes, emphasizing both wireless and infrastructure topics. Mr. Gibbs is under contract to UTD from Ericsson, fulfilling a multi-year commitment. He earned his BSEE ('91) and MSEE ('98) from UTD. Mr. Gibbs has over 30 years of experience in telecommunications, the last 10 of which have been with Ericsson. He has served as session chair and speaker at numerous IEC conferences. He also created and administered regional and state wide high school electronics examinations, and serves on technology advisory boards at both the high school and community college level. A senior member of the IEEE, he was recently honored by UTD's Electrical Engineering department with its 1999-2000 Instructor of Excellence award.

Stefano Basagni holds a Ph.D. in computer science from the University of Milano, Italy (1998). He received his B.Sc. degrees in computer science from the University of Pisa, Italy, in 1991. Since 1997 he has been a senior researcher at the Center for Advanced Telecommunications Systems and Services (CATSS) at The University of Texas at Dallas. Dr. Basagni current research interests concern research and implementation aspects of mobile networks and wireless communication systems, network protocols and distributed algorithms. Dr. Basagni served as a guest editor of the special issue of the Journal on Special Topics in Mobile Networking and Applications (MONET) on Multipoint Communication in Wireless Mobile Networks. He served on Technical Program Committees, including the ACM/IEEE MobiCom TPC, and has served as session chair and organizer at multiple IEEE, ACM and IASTED conferences. Dr. Basagni maintains ongoing collaborations with various companies in the "Telecom Corridor," including Rockwell Collins and Alcatel, in the areas of wireless communication and multimedia.