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DAWN:

Dynamic Ad-hoc Wireless Networks

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13. ABSTRACT (Maximum 13 lines, use the attachment if necessary) The DAWN (Dynamic Ad-hoc Wireless Networks) project is developing a general theory of complex and dynamic wireless communication networks. To accomplish this, DAWN adopts a very different approach than those followed in the past and summarized above. DAWN constitutes what is arguably one of the most ambitious research teams of experts ever assembled that can mount a truly cross-disciplinary approach incorporating the effects of the physical layer explicitly into the modeling, analysis, and control of wireless communication networks. DAWN will systematically redefine and reorganize existing models, protocols and controls, and develop new ones in a framework that guarantees realism and cross-layer consistency to enable the efficient design of such complex wireless systems as those required by the Army. The models, tools, algorithms, and protocols developed in DAWN will provide transformational improvements to the way in which a network-centric battlefield is managed in the future.		
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1 Introduction

The network-centric battlefield is a system of systems encompassing large numbers of sensors and mobile or static elements. Sensors, troop carriers, unmanned air vehicle (UAV), aircraft, smart weapons, soldiers, and command centers are all interconnected in the battlefield and can be reached from wired segments of the Internet. The network-centric battlefield is subject to drastic and continuous changes in radio-link quality, connectivity, the location of nodes and services, and the types of information flows that traverse communication links and nodes.

In theory, ad hoc networking technology should be ideal to support the network-centric battlefield; however, the practice today is far from this theory. Despite the intense past and ongoing research and development work on ad hoc wireless networks, adequate principles, tools, and methodologies for designing reliable MANETs that meet given requirements are still missing. To date, most protocol design and analysis approaches for MANETs have essentially decoupled the “network” from the “physical medium.” The results from this approach have led to the false belief that system theoretic tools (that focus for example on dynamical system behavior) may lead to scalable methods of design and operation. The focus of most protocol-design approaches for MANETs and sensor networks continue to view a network as a graph in which interference at a receiver occurs only over the links with its “one hop” neighbors (those nodes whose transmissions the receiver can decode on the basis of signal attenuation), which leads to the erroneous model that interference is only due to nodes in close proximity to the receiver. These approaches apply methods of analysis that are similar to those used to study the Internet. In reality, interference at a receiver is a complex function of the characteristics of the wireless media and terrain, and the transmissions allowed by the protocol stack from any source in the network. On the other extreme, communication theorists either continue to focus on point-to-point models (or at most on “uplink” or “downlink” models of cellular paradigms) or pose Shannon-theoretic questions for large networks that are as yet impossible to analyze, and provide insight into the design of sparse networks or networks of moderate sizes.

To address the limitations of the current state of the art in the modeling of ad hoc networks and their protocols, the *Dynamic Ad-hoc Wireless Networks (DAWN)* project was established to develop a general theory of complex and dynamic wireless communication networks. To accomplish this, DAWN adopts a very different approach than those followed in the past and summarized above. DAWN constitutes what is arguably one of the most ambitious research teams of experts ever assembled that can mount a truly cross-disciplinary approach incorporating the effects of the physical layer explicitly into the modeling, analysis, and control of wireless communication networks. DAWN will systematically redefine and reorganize existing models, protocols and controls, and develop new ones in a framework that guarantees realism and cross-layer consistency to enable the efficient design of such complex wireless systems as those required by the U.S. Army. The models, tools, algorithms, and protocols developed in DAWN will provide transformational improvements to the way in which a network-centric battlefield is managed in the future.

DAWN is meant to operate as a distributed laboratory with investigators in multiple campuses: (a) working jointly in research and student supervision, (b) ensuring that our re-

search has relevance to the Army and the DoD, and (c) fostering cross-fertilization with other programs. Professor Garcia-Luna-Aceves is the Principal Investigator (PI) of DAWN. The rest of the faculty supported in DAWN are Professor Anthony Ephremides from the University of Maryland (Maryland); Professor Muriel Medard from MIT; Professor Pravin Varaiya from UC Berkeley; Professors Mario Gerla and Rajive Bagrodia from UCLA; Professors Katia Obraczka and Hamid Sadjadpour from UC Santa Cruz (UCSC); Professors Jennifer Hou and Nitin Vaidya from the University of Illinois at Urbana-Champaign (UIUC); and Professor Andrea Goldsmith from Stanford University (Stanford).

The technical approach in DAWN is organized into six tasks. Task 1 addresses mathematical frameworks for the modeling of wireless networks; Professor Ephremides (Maryland) is Task Leader of this task, and Professors Varaiya, Goldsmith, Garcia-Luna-Aceves, Sadjadpour, and Medard participate in it. Task 2 investigates cross-layer interactions and robustness; Professor Andrea Goldsmith (Stanford) is Task Leader of this task, and Professors Medard, Obraczka, Vaidya, Gerla, Sadjadpour, and Bagrodia participate in it. Task 3 focuses on developing a theory of scalable and robust protocols; Professor Garcia-Luna-Aceves is Task Leader for his task, and Professors Gerla, Vaidya, Hou, and Obraczka participate in this task. Task 4 studies energy-efficient networks; Professor Katia Obraczka (UCSC) is Task Leader for this task, and Professors Hou, Medard, Goldsmith, Garcia-Luna-Aceves, Gerla, and Vaidya participate in it. Task 5 addresses large, high-fidelity simulations; Professor Jennifer Hou (UIUC) is Task Leader of the task, and Professors Vaidya and Bagrodia participate in it. Task 6 investigates the modeling and control of information flow patterns; Professor Pravin Varaiya is the task leader, and Professor Ephremides participates in the task.

2 Scientific Progress

This section summarizes the scientific progress made during the second year of the project in establishing a mathematical framework for the modeling of MANETs and sensor networks, exploiting cross-layer interactions in protocol stacks, developing a theory of scalable and robust protocols for MANETs and sensor networks, enabling large and high-fidelity simulations, and introducing novel approaches for network control.

We organize the discussion of our contributions according to the six tasks of DAWN based on the main thrust of each contribution, and present each contribution only once. However, as we did in our prior interim report, it should be noted that the PIs in DAWN have collaborated across multiple tasks and many of the accomplishments in DAWN involve more than a single task.

2.1 Executive Summary

During its second year, the DAWN project has continued making fundamental contributions to the development of a science of networks. The caliber of the contributions made in the project can be easily measured by the quality and quantity of publications and the graduate students who have benefited from the research carried out in DAWN.

We have made remarkable progress in the development of new mathematical frameworks for the characterization of MANETs, which will help researchers and practitioners understand mobile ad hoc networks, and the design of protocols that are much better suited for MANETs. During the second year of the DAWN project, we have had 27 journal papers published or accepted for publication, 51 peer-reviewed papers published or accepted for publication in conference proceedings and books, 3 invited papers published in conference proceedings, and more than 18 manuscripts being considered for publication. While the number of publications achieved by the researchers participating in DAWN is impressive, the quality of the work is even more so. The following five papers received Best Paper or Best Student Paper awards at various conferences:

- Best Paper Award (selected from 404 submissions): J. Boice, J.J. Garcia-Luna-Aceves, and K. Obraczka, “On-demand Routing in Disrupted Environments,” *Proc. IFIP Networking 2007*, Atlanta, GA, May 14–18, 2007.
- Best Paper Award: X. Wu, H. Sadjadpour and J.J. Garcia-Luna-Aceves, “Analytical Modeling of Link and Path Dynamics and Their Implications on Packet Length in MANETs,” *Proc. SPECTS 2007: 2007 Int’l Symposium on Performance Evaluation of Computer and Telecommunication Systems*, San Diego, CA, July 16–18, 2007.
- Best Paper Award (selected from 265 submissions): V. Rajendran, K. Obraczka, and J.J. Garcia-Luna-Aceves, “A DYNAMIC Multi-channel Medium Access Framework for Wireless Ad Hoc Networks,” *Proc. IEEE MASS 2007*, Pisa, Italy, Oct. 9–11, 2007.
- Best Paper Award: Sewook Jung, Uichin Lee, Alexander Chang, Daeki Cho, and Mario Gerla “BlueTorrent: Cooperative Content Sharing for Bluetooth Users,” *Proc. IEEE PerCom 2007*, White Plains, NY, March 19–23, 2007.

- Best Student Paper Award: Chris T.K. Ng, Deniz Gunduz, Andrea Goldsmith, and Elza Erkip, "Minimum Expected Distortion in Gaussian Layered Broadcast Coding with Successive Refinement," IEEE International Symposium on Information Theory (ISIT), Nice, France, June 2007.

Our journal publications appear in some of the most selective journals covering the field of wireless networks, including the IEEE Transactions on Information Theory, the IEEE Transactions on Communications, IEEE JSAC, WINET, and Ad Hoc Networks. It is also worth noting that 12 of the conference papers published this year by DAWN researchers appeared in such technical conferences as IEEE Infocom, ACM Mobicom, and ACM Mobihoc, which are more selective than many technical journals.

In addition, to these publications, six Ph.D. theses and four M.S. theses were completed.

During the past year, we have obtained many novel results on the capacity of wireless networks. Two key results are the computation of the capacity of wireless networks when multi-packet reception is used, and a unifying framework for the capacity of wireless networks subject to any type of information dissemination. We have developed new models to characterize links as a coordinate system and the most accurate analytical model of link and path lifetimes as functions of mobility. We have also obtained new insight on the performance of 802.11 wireless networks and the impact of network coding on the throughput and delay of wireless networks.

We continued to make progress on cross-layer design issues in wireless networks. We have obtained new results on cooperative communication applicable to multiple flows, and the use of an SINR model for topology control.

We continued to investigate new theories of scalable and robust protocols with emphasis on channel access and routing. We investigated spatial contention resolution and MPR-based medium access control schemes, which have great promise in augmenting the maximum throughput in multihop wireless networks. We developed new schemes for multicasting and broadcasting taking advantage of MIMO and meshes (subgraphs that are better connected than trees). We investigated the use of practical network coding schemes to improve the performance of multicasting, link-level, and transport-level protocols. We extended the traditional on-demand routing schemes defined for connected ad hoc networks to the case of networks with disruption, where there need not ever be end-to-end connectivity from source to destination. Finally, we extended traditional routing designs that focus on destinations by applying ordering constraints that apply to relations among nodes, such as source-destination pairs.

We obtained novel results on energy-efficient networks that range from the development of new models making use of SINR for power and rate control in channel access to the design and analysis of methods of using control knobs at the physical (PHY) and medium access control (MAC) levels and specific channel access scheduling schemes.

We made considerable progress on simulation, emulation and testing techniques that in the future will enable very large-scale simulations based on correct and efficient characterizations of the physical layer and its interaction with the protocol stack of a MANET.

Lastly, we developed new models of information flow patterns in wireless networks by applying game theory to stochastic routing, developing new models for localization and sam-

pling in sensor networks, and obtaining new models for epidemic dissemination in vehicular networks.

In short, the DAWN project has continued delivering tangible and fundamental results in the problem areas identified by the U.S. Army Research Office in the “science of networks” challenge. The rest of this section summarizes the technical accomplishments in each task of the project.

2.2 Task 1: Mathematical Modeling Frameworks

In this task, we have made several contributions on the modeling of ad hoc networks. These contributions include: (a) The first results on the capacity of wireless networks when nodes use multi-packet reception, (b) a unifying modeling framework for the capacity of wireless networks subject to any type of information dissemination, (c) new results on multi-channel network performance in the presence of constraints on channel-switching, (d) modeling of links as network coordinates, (e) the most accurate analytical models of link and path lifetimes to date, (f) the first statistically-equivalent model to characterize random waypoint mobility commonly used in simulations, (g) more accurate performance models for 802.11 channel access, and (h) new results on the impact of network coding on the stable throughput and delay in wireless networks. The rest of this section provides more information about each contribution.

2.2.1 The Capacity of Wireless Networks

In this part of our research, we have investigated the following three areas:

- The capacity of wireless networks when the nodes of the network are endowed with multi-packet reception (MPR) capabilities.
- A unifying modeling framework for the capacity of wireless networks subject to any type of information dissemination (unicasting, multicasting, broadcasting and anycasting).
- Performance limits of multi-channel networks in the presence of constraints on channel-switching.

Capacity of Wireless Networks with MPR: During the past year of performance, we completed the analysis of the many-to-many communication scheme for MANETs that we introduced last year. Many-to-many communication is an opportunistic cooperation scheme that allows multiple nodes to communicate with each other when they are within each other communication range.

A careful examination of our many-to-many communication scheme reveals that it is a combination of multi-copy forwarding [3] and multi-packet reception (MPR) [4] techniques. Based on this observation, we have started to investigate the capacity of wireless ad hoc and sensor networks when each node is endowed with MPR capability. We have demonstrated that the per source-destination throughput $T(n)$ of a random wireless ad hoc network of

three dimensions (or 3-D network) in which nodes utilize MPR is bounded by $\Theta(r(n))$ (upper and lower bounds) with high probability (i.e., with probability 1 when $n \rightarrow \infty$) when the protocol model is used, where $r(n)$ is the reception range of a receiver. This result is quite remarkable and yet intuitive! First, we note that, to ensure connectivity in random wireless ad hoc networks, $r(n) \geq \Theta\left(\sqrt[3]{\log n/n}\right)$. This results in an achievable bound of $\Theta\left(\sqrt[3]{\log n/n}\right)$ for a random wireless ad hoc network endowed with MPR in its nodes, which represents a gain in the order capacity of $\Theta(\log(n))$ compared to that attained with simple multihop routing [1, 2] (one-to-one communication) or NC [8]. Second, our result is in stark contrast to all existing results in ad hoc networks assuming point-to-point communications! It states that *increasing* the communication range $r(n)$ actually *increases* the capacity of an ad hoc network. Intuitively, the reason for this is that, given that all receivers are endowed with MPR, MAI around any receiver becomes useful information and no longer decreases the capacity. Clearly, the restrictions in choosing the communication range among nodes are: (a) the need to maintain connectivity in the network, which provides a lower bound on $r(n)$; and (b) the energy spent per transmission, the transmitter complexity, and the decoding complexity of the nodes in the network, which provides a practical upper bound on $r(n)$.

Furthermore, we have shown that, in a wireless ad hoc network in which optimum routing is known to all sources and a combination of multi-pair unicasting and a single-source multicasting to a small group take place, MPR provides a gain in the order capacity of the network compared to NC. Intuitively, this can be explained by noticing that the percentage of multicast traffic becomes smaller compared to the multi-pair unicasts as the number of nodes increases, and then applying the results by Liu et al. [8] and our result on the capacity of wireless networks with MPR.

Our capacity demonstrate that MPR can have a tremendous impact on the performance of future ad hoc networks, because it enables the protocol architectures of such networks to be based on many-to-many communication, which takes advantage of the broadcast nature of wireless links and the peer-to-peer nature of nodal interaction. However, turning these theoretical results into practice represents a big challenge. In practice, receivers can decode only a finite number of concurrent transmissions, rather than all the transmission that occur within their reception range. Therefore, trade-offs are needed between the added efficiency attained by means of concurrent transmissions, and the added cost incurred by the complexity of the receivers that must process such transmissions. Furthermore, the communication protocols used to date in ad hoc networks have been designed to avoid MAI, and are derivatives of protocols and architectures originally designed for wired networks based on point-to-point links. For example, today's popular IEEE 802.11 DCF can be viewed as attempting to emulate "Ethernets in the sky" in that at most one transmission is allowed to reach a receiver, and senders are forced to back off in the presence of MAI. Similarly, the IETF MANET routing protocols are based on the assumption that packets are to be forwarded along single paths, and they work independently of the channel access method, even though it is *not* true that routing in MANETs occurs over a pre-existing network topology and the transmission over one link does not impact the transmissions over other links, as it can be done in a wired network.

Therefore, for MPR to really help ad hoc networks scale (i.e., an increase in capacity over

today's approaches in the order of the degree of nodes in the network), the protocols used in such networks have to be redesigned from the ground up to *embrace*, not combat, MAI. We believe that this constitutes a major challenge for the Army and the research community at large, and that solutions to this challenge can one day render truly scalable ad hoc networks.

The above results are reported in the ITA07 and MOBICOM 2007 conferences. Moreover, we have also pointed out that the gap in the lower and upper bounds of capacity for wireless ad hoc networks with the physical model assumption can be closed using MPR achieving higher order capacities than what has been reported in the literature [5].

A Unifying Framework for the Capacity of Wireless Networks: We have also started investigating the application of graph theory in computing capacity and delay trade-offs for wireless ad hoc networks. Our investigation has resulted in the first unified modeling framework for the computation of the throughput capacity of random wireless ad hoc networks in which information is disseminated by means of unicast routing, multicast routing, broadcasting, or different forms of anycasting. More specifically, we define (n, m, k) -casting as a generalization of all forms of one-to-one, one-to-many and many-to-many information dissemination in wireless networks. In the context of (n, m, k) -casting, n , m , and k denote the number of nodes in the network, the number of destinations for each communication group, and the actual number of communication-group members that receive information (i.e., $k \leq m$), respectively.

With our new framework, we demonstrate that the capacity of wireless ad hoc networks for any type of information dissemination can be derived with our unified approach using the (n, m, k) -cast formulation. Our results on the (n, m, k) -cast capacity of a random wireless network unifies existing results on the order capacity of wireless networks subject to unicasting [1], multicasting [13, 14, 15], or broadcasting [9, 10, 11, 12], provides new capacity results for anycasting and manycasting, and helps to develop new insight on the role of route signaling and in-network storage on the capacity of ad hoc networks. We have shown that the capacity of wireless ad hoc networks depends greatly on the number of destinations m . We introduce two important thresholds in our framework, $m_u = \Theta(1)$ and $m_b = \Theta\left(\frac{n}{\log n}\right)$, and show that when $m \leq m_u$, the capacity behaves similar to unicast even when all communications are multicast. When $m_u < m < m_b$, then the capacity is similar to that of multicast and finally, for $m \geq m_b$, the capacity of wireless ad hoc networks is equivalent to that of broadcast regardless of the number of destinations and as long as it is greater than m_b . We also show that anycasting and manycasting provide higher order capacity than unicasting when $k < \sqrt{m}$.

This modeling framework opens up new areas of research related to anycasting (routing to or from any one of the nodes in a communication group) "manycasting" (routing to or from a subset of the nodes in a communication group), and the effect of route control signaling on the scaling properties of wireless networks. An important observation to be made regarding the behavior of $C_{m,k}(n)$ as a function of m is that, in a real wireless network, data dissemination occurs together with route signaling. The issue is that, in practice, all unicast and multicast routing protocols involve some form of broadcasting (e.g., flooding of link-state updates, propagation of route requests or join requests, or diffusion of distance updates). Hence, the scaling properties of an ad hoc wireless network is really determined by

the dominating form of information dissemination, which may occur for control signaling or data. Accordingly, in order for future wireless ad hoc networks to have the best possible scaling properties, it is clear from our results that the number of nodes impacted by any one route signaling packet on the average should be bounded by $\Theta(1)$. One possible approach for scale-free route signaling is to ensure that only those nodes who actually have an interest in the routes for which a signaling packet is needed receive the signaling packet. Clearly, this poses a challenge, because no distributed oracle exists with instantaneous knowledge of what control information each node needs. However, such an interest-driven signaling can be an important ingredient for scalable wireless ad hoc networks.

Another result derived from the behavior of $C_{m,k}(n)$ as a function of m is that anycasting and multicasting render a higher order capacity than unicasting when the number of destinations in the communication group of a source that actually receive the information from the source is $k < \sqrt{m}$. This indicates that capacity increase can be attained by an appropriate use of in-network storage and information dissemination from the nearest site(s) of a communication group to the group source (the node with interest in the information), rather than from pre-defined origins hosting the content. If the communication group is the entire network ($m = n$), information flows from the closest neighbor(s) to each node and the maximum capacity gain is attained. If the group size is independent of the size of the network ($m = \Theta(1)$), the order capacity is the same as for unicasting.

These results have been submitted for publication to INFOCOM 2008. During the next period of performance, we will attempt to compute the throughput capacity of wireless ad hoc networks in broadcast and multiple source multicast applications for MPR and NC. To date, these issues are open problems. These results will provide crucial inside to the Army in deciding on future research and development directions for wireless ad hoc and sensor networks.

Multi-Channel Wireless Networks: In our previous annual report, we reported on our capacity results for the case of multi-channel wireless networks with switching constraints. This work is motivated by the need for low-cost, low-power radio transceivers, which may have constrained switching capabilities. We address the issue of multi-channel network performance in the presence of constraints on channel-switching. In such cases, we study connectivity and capacity of a wireless network comprising n randomly deployed nodes, equipped with a single interface each, when there are $c = O(\log n)$ channels of equal bandwidth $\frac{W}{c}$ available. In our previous annual report, we reported that for a random (c, f) channel assignment, wherein each node may switch between a pre-assigned random subset of f channels, *per-flow* capacity is $O(W \sqrt{\frac{p_{rnd}}{n \log n}})$ (where $p_{rnd} = 1 - (1 - \frac{f}{c})(1 - \frac{f}{c-1}) \dots (1 - \frac{f}{c-f+1})$) and $\Omega(W \sqrt{\frac{f}{cn \log n}})$, with the conjecture being that it is $\Theta(W \sqrt{\frac{p_{rnd}}{n \log n}})$. Subsequently, we have been able to prove the correctness of the above conjecture. In addition, we have investigated other constrained channel assignment models. In particular, we have considered a model in which the channels are organized in a matrix, and each node is able to switch on all channels in one row, and one channel in each of the other rows. This channel assignment ensures that each pair of nodes share a channel, improving network connectivity, and performance.

In addition to capacity results, we are also investigating design of cross-layer protocols that can achieve network utility maximization (NUM) in a multi-channel wireless network. We have built on past work on NUM to incorporate the availability of multiple channels as well as multiple interfaces, by introducing the notion of virtual links within each node in the network. Preliminary results using this approach suggest that it is possible to achieve most of the performance benefit of the multiple channels while utilizing a relatively small number of interfaces.

We plan to continue building on our past work on multi-channel wireless networks, developing practical mechanisms that are motivated by the theory.

2.2.2 Characterizing Links as Network Coordinates

The delivery ratio of wireless is not a direct function of the geographical distance between the link end points. Accordingly, a research question is what is a better link characterization (or how to characterize the neighbor abstraction) and whether or not one can still represent the network topology as a coordinate system.

Different candidate attributes have been proposed to characterize the neighbor abstraction for different purposes. To determine the best route metrics for the purpose of routing, the RTT, the packet loss rate, the expected transmission time (ETX), and the weighted cumulative expected transmission time (WCETT) have been proposed to characterize the link/path quality. To determine the level of interference between nodes, the *received signal strength (RSS)* has been proposed. We believe there may not be a single attribute that serves all the purposes, and at times a combination of several attributes may be the best. However, we believe a *new* coordinate system should be devised to appropriately characterize the neighbor abstraction with respect to one or more attributes. To this end, we characterize the *location* of a node \mathbf{n} in a virtual coordinate system, *with the set of measurements it makes between itself and nodes whom it can receive signals*. Let's use the RSS measurement as an example.

Let $\mathcal{M}(n)$ denote the set of nodes that can directly communicate with \mathbf{n} and \mathbf{n} itself. Then, the RSS measurements between \mathbf{n} and nodes in $\mathcal{M}(n)$ can be written in an $p \times p$ square matrix $\mathbf{S} = [s_{ij}]$ for $i, j \in \{1, \dots, p\}$, where s_{ij} is the (-RSS) measurement made in dBm by the i th node to j th node, $s_{ii} = 0$, and $p = |\mathcal{M}(n)|$ is the number of nodes. The columns of \mathbf{S} can be considered as the coordinates of the corresponding nodes in a p -dimension space. There are, however, three issues to be considered: (i) the dimension p may be large; (ii) these coordinates are likely to be correlated with each other, and hence it becomes difficult to identify components that play an important role; and (iii) the coordinate system has to be properly augmented to include nodes that cannot directly communicate with node \mathbf{n} .

To tackle these research issues, we construct, with principal component analysis (PCA), a virtual coordinate system that represents the *neighbor abstraction* with a smaller dimension.

We use singular value decomposition (SVD) to determine principal components. Specifically, the SVD of \mathbf{S} is obtained by $\mathbf{S} = \mathbf{U} \cdot \mathbf{W} \cdot \mathbf{V}^T$, where \mathbf{U} and \mathbf{V} are column and row orthogonal matrices, $\mathbf{W} = \text{diag}(\sigma_1, \sigma_2, \dots, \sigma_p)$, and σ_i 's are the singular values of \mathbf{S} in the decreasing order (i.e., $\sigma_i \geq \sigma_j$ if $i < j$). Note that $\mathbf{S}^T \mathbf{S} = (\mathbf{U} \mathbf{W} \mathbf{V}^T)^T (\mathbf{U} \mathbf{W} \mathbf{V}^T) = \mathbf{V} (\mathbf{W}^T \mathbf{W}) \mathbf{V}^T$. This means that the eigenvectors of $\mathbf{S}^T \mathbf{S}$ make up \mathbf{V} with the associated (real nonnegative) eigen-

values of the diagonal of $\mathbf{W}^T \mathbf{W}$. Similarly, $\mathbf{S}\mathbf{S}^T = \mathbf{U}^T (\mathbf{W}\mathbf{W}^T) \mathbf{U}$. The columns of the $p \times p$ matrix $\mathbf{U} = [\mathbf{u}_1, \dots, \mathbf{u}_p]$ are the principal components and the orthogonal basis of the new subspace. By using the first q columns of \mathbf{U} denoted by \mathbf{U}_q , we project the p -dimensional space into a new q -dimensional space:

$$\mathbf{c}_i = \mathbf{U}_q^T \cdot \mathbf{s}_i = [\mathbf{u}_1, \dots, \mathbf{u}_q]^T \cdot \mathbf{s}_i, \quad (1)$$

where \mathbf{c}_i is the new coordinate of the i th node, and \mathbf{s}_i is the i th column vector of \mathbf{S} .

After the coordinates of nodes in $\mathcal{M}(n)$ are determined, we need to further determine the coordinate of a node \mathbf{k} that cannot directly communicate with \mathbf{n} but can via node(s) in $\mathcal{M}(n)$. Conceptually, this can be done with the use of RSS measurements made between node \mathbf{k} and relay nodes that can directly communicate with node \mathbf{n} . For example, if $|\mathcal{M}(\mathbf{n}) \cap \mathcal{M}(\mathbf{k})| \geq q + 1$, we may obtain the coordinate of \mathbf{k} , \mathbf{x}_k , by minimizing the objective function: $J_2(\mathbf{x}_k) = \sum_{i \in \mathcal{M}(\text{GN}) \cap \mathcal{M}(\mathbf{k})} (L(\mathbf{x}_i, \mathbf{x}_k) - s_{ik})^2$. In some sense, construction of the virtual coordinate system proceeds in a ring-by-ring manner, starting from the innermost ring composed of nodes in \mathcal{M} and proceeding outward.

We believe the coordinate system thus constructed can be used essentially in the *same* manner as the physical Euclidean coordinate system is used to analyze the wireline network. For example, we can select appropriate attributes that best account for the link/path quality and construct a global, virtual coordinate system in which the distance between two mesh nodes approximately represents the measured path quality. The virtual coordinate system can then be used as the underlying “topology” for unicast/multicast routing. In this case, a node computes its distance to gateway nodes in the virtual coordinate system, and selects the one with the smallest “distance.” For another example, if the set of RSS measurements is used to characterize the neighbor abstraction, the virtual coordinate system constructed will capture the level of interference between nodes – if two nodes are close to each other in the coordinate system, their transmissions will likely interfere with each other.

2.2.3 Analysis of Link and Path Dynamics in MANETs

The communication protocols of mobile ad hoc networks (MANET) must cope with frequent changes in topology due to node mobility and the characteristics of radio channels. From the standpoint of medium access control (MAC) and routing, node mobility and changes in the state of radio channels translate into changes in the state of the wireless links established among nodes, where typically a wireless link is assumed to exist when two nodes are able to decode each other’s transmissions.

The motivation for this part of our research in DAWN is that, while the behavior of wireless links is critical to the performance of MAC and routing protocols operating in a MANET, no analytical model exists today that accurately characterizes the lifetime of wireless links, and the paths they form from sources to destinations, as a function of node mobility. As a result, the performance of MAC and routing protocols in MANETs have been analyzed through simulations, and analytical modeling of channel access and routing protocols for MANETs have not accounted for the temporal nature of MANET links and paths. For example, the few analytical models that have been developed for channel access protocols operating in multihop ad hoc networks have either assumed static topologies (e.g.,

[16]) or focused on the immediate neighborhood of a node, such that nodes remain neighbors for the duration of their exchanges (e.g., [17]). Similarly, most studies of routing-protocol performance have relied exclusively on simulations, or had to use limited models of link availability (e.g., [18]) to address the dynamics of paths impacting routing protocols (e.g., [19]).

Our work has resulted in the most accurate analytical model of link and path behavior in MANETs to date, and characterizes the behavior of links and paths as a function of node mobility. The importance of this model is twofold. First, it enables the investigation of many questions regarding fundamental tradeoffs in throughput, delay and storage requirements in MANETs, as well as the relationship between many crosslayer-design choices (e.g., information packet length) and network dynamics (e.g., how long links last in a MANET). Second, it enables the development of new analytical models for channel access, clustering and routing schemes by allowing such models to use link lifetime expressions that are accurate with respect to simulations based on widely-used mobility models.

Recently, Samar and Wicker [20, 21] pioneered the work of analytical evaluation of link dynamics. They further provided good insights on the importance of an analytical formulation of link dynamics to the optimization of the protocol design. However, Samar and Wicker assume that communicating nodes maintain constant speed and direction in order to evaluate the distribution of link lifetime. This simplification overlooks the case in which either of the communicating nodes changes its speed or direction while the nodes are in transmission range of each other. As a result, the results predicted by Samar and Wicker's model could deviate from reality greatly, being overly conservative and underestimating the distribution of link lifetime [20, 21], especially when the ratio R/v between the radius of the communication range R to the node speed v becomes large, such that nodes are likely to change their velocity and direction during an exchange.

Our approach is based on a two-state Markovian model that reflects the movements of nodes inside the circle of transmission range and builds an analytical framework to accurately evaluate the distribution of link lifetime. Our model subsumes the model of Samar and Wicker [20, 21] as a special case, and provides a more accurate characterization of the statistics of link lifetime. This work started last year and this year we have finished the analysis of MANETs for both restricted and unrestricted mobility cases. Moreover, we have shown that this analytical tool can be used to compute optimum packet length that can either maximize throughput or reliability. We have also shown capacity-delay-storage trade-offs for these systems using the results obtained from link and path lifetime analysis. Our results corroborate previously reported results and it gives some new understanding of the network behavior.

Our contributions have resulted in several conference and journal papers [22, 23, 24]. One of these papers [24] received the Best Paper Award at the SPECTS 2007 Symposium.

We have also recently succeeded in extending the results from this work to analytically evaluate the performance of proactive routing protocols. Such result will enable us to correctly and analytically determine the overhead related to proactive routing protocols. Our first contribution on evaluating proactive routing protocols was accepted for presentation at the MASS 2007 conference [25]. During the next performance period, we will attempt to obtain analytical tools to predict the behavior of MANETs in which different routing

protocols are used.

2.2.4 Mobility Models

We developed the first statistical-equivalent model to characterize random waypoint mobility [88]. By fitting a statistical model to the output of a network simulator, SEMs provide an efficient way to quickly explore the simulator’s result. The proposed random waypoint mobility SEM captures speed decay over time as a function of maximum speed and terrain size. A direct result from our model is that, by characterizing average node speed as a function of time, it provides an accurate estimate of how long of a “warm-up” period simulations employing the random waypoint mobility model need. Recent studies show that under the random waypoint mobility regime, average node speed tends to zero in steady state. They also show that average node speed varies considerably from the expected average value for the time scales under consideration in most simulation analysis. Therefore, using the results from our random waypoint mobility SEM, simulation data from the “warm-up” period can then be discarded to obtain accurate protocol performance results.

2.2.5 MAC-Layer Performance in IEEE 802.11 Networks

References [125, 126] study the MAC layer performance of 802.11 and 802.15.4 CSMA/CA networks. Both papers develop an analytical approach based on a per station Markov model to capture the state of each station at each moment in time. The Markov model yields formulas for throughput and energy which are then validated by comparison with simulations: [125] uses an OPNET simulation; [126] uses a Matlab simulation.

Both papers use the form of argument established by Bianchi [123], with significant differences. In [125], the independent per station Markov models are coupled by their common probability of transmission; in [126] stations have a common probability of attempting its carrier channel assessment (CCA) for the first time within a slot. The MAC layers of the 802.11 and 802.15.4 are different: in the former a station continuously senses the channel; in the latter a contending station wakes up to listen to the channel during maximally two backoff slots. The 802.15.4 MAC layer seeks to minimize energy consumption, the 802.11 MAC layer is concerned with reducing collisions in medium access.

The objective in [125] is to understand how throughput of *all* stations is affected by differences in their data rate, which may arise because of differences in SNR. Since the 802.11 MAC protocol equalizes probability of transmission of each station, stations with a lower transmission rate will bring down the throughput of those with a higher data rate. The derived formulas are then used to propose a simple and standard-compliant algorithm to utilize the channel fairly. The scheme adjusts the packet size according to the data rate. With this scheme, stations occupy the channel for equal amounts of time. An extension to a frame aggregation scheme to show how different packet sizes affect performance.

The analysis in [126] calculates the stationary distribution of the Markov state to determine the relationship between throughput and energy consumption for different settings of the ‘Battery Extension’ parameter for different packet sizes. Two significant conclusions are reached. First, with ‘Battery Extension’ more packets are sent, but less net throughput is

achieved and a lot of energy and channel resources are wasted in collided transmissions. For sensor networks that are expected to generate a lot of traffic across the nodes simultaneously, BE should be as large as possible. Second, for low load the energy per useful bit steadily decreases; for higher loads, the net throughput decreases because of increased collision. The average power consumption increase with rate is mainly because of the increased Tx power but also because of increased CCA power consumption.

2.2.6 Performance Impact of Network Coding

We have examined two issues associated with using Network Coding in ad hoc networks. The first one concerns the stable throughput region in simple wireless multicast systems and the second one concerns the effects of Network Coding on Packet Delay.

It should be noted that we consider only Random Linear Coding since it has been proven that all benefits of Network Coding can be realized through the use of this simple and tractable form of packet combination. Specifically, Random Linear Coding involves simply adding (modulo 2) the contents of the packets that are merged, each weighted with a binary coefficient chosen randomly and independently for each packet and each transmission. A more general (but equivalent) version is to enlarge the alphabet size of the field and use coefficients from that field adjusting appropriately the representation of the packets and their "addition". The key difference of our approach from other work on wireless network coding is the focus on stability and, hence, on models in which each node has a buffer in which generated and/or received packets accumulate randomly. The objective of stability is to keep the delay finite (necessary and (almost) sufficient condition for which is for the queue size to be positive recurrent if the arrival and service models have Markovian properties (which they do in our models)). Thus, random linear coding in this set-up consists of transmitting at each slot a random linear combination of the entire contents of the buffer. This is in fact the prevalent use of Network Coding for content distribution.

Multicast Throughput Regions: We consider two source nodes, each of which must multicast its messages to the same two receivers. Packets arrive at source i ($i=1,2$) with Bernoulli rate $r(i)$ and in each slot each of the two transmitters attempts transmission of the head-of-the-line packet with probability $p(i)$. The probability that a transmitted packet from source i is successfully received at receiver j is $q(i,j)$. Thus we model the multicast medium as a packet erasure channel. In addition we permit (through some form of multi-user detection) the simultaneous successful reception of two packets at the same destination. This model is a non-trivial generalization of the classic interacting-queue system that has been studied extensively in the literature for multi-access channels. The first option is to use a simple ARQ-type protocol in which each packet is successively retransmitted until both receivers acknowledge successful reception. Then it is removed from the queue and the next packet is transmitted. The Network Coding option is to combine through the Random Linear coding scheme K packets from the queue (an independently chosen combination each time for the same K packets) and transmit that in each slot. There will be a need for $N(k)$, with $N(k)$ clearly greater than or equal to k , successfully received packets to decode k of them. As soon as both receivers acknowledge successful reception of the entire block of K packets, that

block is removed from the queue and each transmitter starts the transmission of a linear combination of the next block of K packets. This "gated" type of Network Coding is clearly suboptimal since it is possible for the transmitter NOT to possess in its buffer at a given time K packets and therefore it may have to wait until a block of K packets is completed. This is why the free-form of combining the entire contents of the buffer is preferable. However, the analysis of the latter is intractable. Note that the employment of the "gated" model does affect both stability and delay. However, the phenomenon of idling while waiting for a block of K packets to form does not occur as the arrival load on the system increases. The reason is that, as the queues get longer and the system saturates, there will always be sufficient numbers of packets to combine for any finite value of K .

We obtained the stability region for this model. That is, we identified the set of values of $r(1)$ and $r(2)$ for which the delay is finite. Interestingly, the shape of the stable throughput need not be concave or convex. In fact, the shape depends on the quality of the channel. As K is allowed to increase the stable throughput region does appear to approach the Information-theoretic capacity of the channel. Without the use of Network Coding however, that is when $K=1$, the stability region is considerably smaller than the capacity region, as documented in our recent paper published in the August 2007 issue of the IEEE Transactions on Information Theory.

Delay: We then analyzed the queueing delay for each terminal in the model described above. Here we focused on a single link to capture the properties of the "gating" that Network Coding introduces and to avoid the complexity of the interaction among the queues. We were successful in analyzing this queueing model and found that for underloaded systems the delay is insensitive to the value of K . However, as the arrival rate increases, the system saturates earlier when $K > 1$ than when $K=1$. This observation leads to the interesting conclusion that network coding does not reduce delay in a single link system and in fact saturates at lower rates than a simple retransmission system. The advantage of network coding noted before in the stable throughput region analysis stems from the fact that network coding "hedges" channel behavior in the multicast case and this is why it is well-suited to multiple destination systems. Nonetheless, it is interesting that as K approaches infinity the delay performance of the single-link system approaches that of the simple retransmission (ARQ-like) system.

Related Cooperative Communication Studies: We have followed a number of approaches to the use of Network Coding (or other forms of cooperation among nodes) in wireless networks. We have considered the effect of adversarial node behavior exemplified either via selfishness (ie individual utility function optimization for each node) or via malicious behavior (ie zero-sum game behavior). We have studied the effect of such behavior on stable throughput with or without Network Coding. We have also considered network-level use of relays in which idle slots are utilized by relaying nodes to increase stable throughput. Both of these works are documented in the referenced (and attached) papers, one of which was published in the JSAC special issue on Cooperative Techniques and the other one will appear in the upcoming special issue of the IEEE Transactions on Information Theory, again on Cooperative Techniques.

2.3 Task 2: Cross-Layer Interactions and Robustness

This past year we have focused on several different aspects of crosslayer interaction and robustness as well as cooperative communication in wireless ad hoc networks.

2.3.1 Cross-Layer Design and Coding

We have completed our work on cross-layer protocol design for real-time media over ad hoc wireless networks. This work is based on characterizing the diversity-multiplexing tradeoff region in multiple antenna wireless systems and networks to find the point on this region that minimizes end-to-end distortion [26]. The goal is to find the optimal balance between the increased data rate provided by multiplexing versus the error protection provided by diversity. We have shown that in the high-SNR asymptotic regime we can find a closed form expression for the end-to-end distortion as a function of the optimal point on the diversity-multiplexing tradeoff curve. Moreover, for large but finite SNR, this optimal point can be found via convex optimization. We also used the same general framework to minimize end-to-end distortion for a broad class of practical source and channel codes, including progressive video encoding and space-time channel codes. Finally, we have incorporated delay into this framework via retransmission and ARQ, thereby obtaining the three-dimensional diversity-multiplexing-delay tradeoff which we optimize to minimize end-to-end distortion for delay-constrained source data.

We have also been working on several aspects of cross-layer source and channel coding to minimize end-to-end distortion. Specifically, in [27, 28], we investigate the case when a transmitter without channel state information (CSI) wishes to send a delay-limited Gaussian source over a slowly fading channel. The source is coded in superimposed layers, with each layer successively refining the description in the previous one. We determine the optimal layering and optimal power distribution that minimizes the expected distortion. We find that while expected distortion can be improved by acquiring CSI at the transmitter (CSIT) or by increasing diversity from the realization of independent fading paths, at high SNR the performance benefit from diversity exceeds that from CSIT. Another aspect of this problem is examined in [29], where we consider a layered approach to source coding such that the decoder receives a compressed version of the symbol at a given rate, as well as an uncompressed version over a separate side-information channel with slow fading and noise. The decoder knows the realization of the slow fading but the encoder knows only its distribution. We consider a layered encoding strategy and utilize the Heegard-Berger rate-distortion function to optimize the layers based on the fading distribution. Under discretized Rayleigh fading, we show that the optimal rate allocation puts almost all rate into the base layer associated with the worst-case fading. This implies that uncertain side information yields little performance benefit over no side information. We also show that as the source coding rate increases, the benefit of uncertain side-information decreases. The last area of cross-layer optimization we consider is source/channel coding over a relay channel. Specifically, in [30] we consider transmission of a Gaussian source over a Gaussian relay channel, where the relay terminal has access to correlated side information. We propose several cooperative joint source-channel coding strategies that utilize both the broadcast nature of the wireless transmission and/or the availability of the correlated side information at the relay, and compare these to

distortion lower bounds obtained by the cut-set arguments. In general, the best performing scheme depends on the correlation among the source and the relay signals, and the average link qualities. In particular we show that our proposed strategies achieve near-minimum end-to-end distortion in most cases.

2.3.2 Cooperative Communication

Another main thrust of our work this past year has been on cooperative communication and relaying in wireless networks. In particular, in [31, 32] we investigate information-theoretic relaying for unicast and multicast in wireless networks. Sophisticated relaying strategies at the physical layer have been developed for a single flow, but multiple flows are typically handled by time sharing the channel between the flows at the network level. In this work we investigate joint relaying and generalized forwarding (analog network coding) that allows the relay to combine data streams for both unicast and multicast traffic. We show that joint relaying and analog network coding can achieve gains and even double the throughput for certain channel conditions over other existing techniques. Our work in [33, 34] exploits the broadcast nature of the wireless channel to encode at one transmitter based on what is heard from another transmitter, a technique also referred to as cognitive radio. In particular, we obtain both upper and lower bounds on the capacity limits of such cognitive transmission. Our achievable strategies beat all known techniques for this channel and demonstrate significant gains over noncooperative schemes. In [35] we investigate strategies for symmetric cooperation, where both transmitters cooperate to send information to their desired receivers. We show in this work that, assuming all transmitters and receivers have full CSI, transmitter cooperation generally works much better than receiver cooperation in terms of increasing data rates, in part because it can exploit dirty paper coding. Finally, in [36] we investigate the impact of CSI and power control on transmitter and receiver cooperation. With CSI and power control, transmitter cooperation is best, similar to in [35], because dirty paper coding can be used. However, in the absence of CSI, transmitter cooperation does worse than receiver cooperation, and without CSI or power control cooperation yields no performance gains. The combination of [35, 36] give significant insight into when cooperation increases capacity and what system assumptions must be in place for this increase to occur.

2.3.3 Topology Control under The SINR Model

Topology control and management – how to determine the transmit power of each node so as to maintain network connectivity, mitigate interference, improve spatial reuse, while consuming the minimum possible power – is one of the most important issues in wireless multi-hop networks. Instead of transmitting using the maximal power, wireless nodes collaboratively determine their transmit power and define the topology by the neighbor relation under certain criteria.

A common notion of neighbors adopted in most topology control algorithms, perhaps except those in Zollinger et al., is that two nodes are considered as neighbors and a wireless link exists between them in the corresponding communication graph, if their distance is within the transmission range (as determined by the transmit power, the path loss model, and the receiver sensitivity) of each other. Algorithms that adopt this notion are collectively

called *graph-model-based topology control*. Under this notion, topology control aims to keep the node degree in the communication graph low, subject to the network connectivity requirement. This is based on the common assertion that a low node degree usually implies low interference.

We claim that this assertion no longer holds under the physical *Signal-to-Interference-Noise-Ratio (SINR)* model. This is because under the physical model, whether the interference affects the transmission activity of interest depends on the SINR at the receiver, which in turn depends on the transmit power of all the transmitters and their relative positions to the receiver of interest. The node degree under the graphic model, however, does not adequately capture interference. In particular, a transmission of interest may fail because other concurrent transmissions cause the SINR at the receiver to fall below the minimal SINR required for the receiver to decode the symbols correctly. This could occur even if competing transmitters are outside the transmission range of the receiver. There are two undesirable consequences as a result of the inadequacy of graph-model-based topology control under the physical model. First, because the node degree does not capture interference adequately, the interference in the resulting topology is likely to be high, which leads to low network throughput. Second, a wireless link that exists in the communication graph may in practice not exist under the physical model, because of high interference (and consequently low SINR). As a result, the network connectivity may not even be sustained.

In this part of project, we first formally argue that a node with a small node degree in the communication graph may suffer from high interference. Note that Burkhart et al. have made similar claims by defining interference based on the *interference range* of the link of interest. In contrast, we measure the interference by the *interference degree*, which reflects the number of nodes that actually interfere the transmission over the link of interest. Then, we define the interference graph that faithfully captures interference under the physical model. An interesting question is whether or not there exists a power assignment that enables the communication graph of the topology to represent its interference graph as well. We formally prove that such a power assignment exists only if the topology satisfies a certain criterion. Unfortunately, most of the topologies generated by existing graph-model-based topology control do not satisfy this criterion.

To enable effective topology control under the physical SINR model, we propose a centralized approach, called **Spatial Reuse Maximizer (MaxSR)**, that consists of two component algorithms: **T4P** and **P4T**. Conceptually, given the topology induced by certain topology control algorithm, each node may, instead of using the minimal possible power to reach its farthest neighbor (as defined in the communication graph), increase its transmit power in order to increase the SINR at the receiver and better tolerate interference. On the other hand, if every node transmits with higher transmit power, it contributes more to the interference as perceived by other nodes. **MaxSR** seeks to strike a balance between increasing the SINR and controlling the interference as perceived by others to an acceptable level. Specifically, **T4P** optimizes assignment of the transmit power given a fixed topology, where by optimality we mean that the transmit power is so assigned that it minimizes the average interference degree (defined as the number of nodes that will interfere with transmission on a link), and (ii) **P4T** constructs, based on the power assignment made in **T4P**, a new topology by deriving a spanning tree that gives the minimal interference degree. By alternately invoking

the two algorithms, the power assignment quickly converges to an operational point that maximizes network capacity. We formally prove the convergence of **MaxSR**, and show via simulation that the topology induced by **MaxSR** outperforms that derived from existing topology control algorithms by 50-110% in terms of maximizing network capacity.

2.4 Task 3: Theory of Scalable and Robust Protocols

In this task, we investigated new theories of scalable and robust protocols with emphasis on channel access and routing. We investigated spatial contention resolution and MPR-based medium access control schemes, which have great promise in augmenting the maximum throughput in multihop wireless networks. We developed new schemes for multicasting and broadcasting taking advantage of MIMO communication, network coding, and the use of multicast meshes. We investigated the use of practical network coding schemes to improve the performance of link-level, and transport-level protocols. We extended the traditional on-demand routing schemes defined for connected ad hoc networks to the case of networks with disruption, where there need not ever be end-to-end connectivity from source to destination. lastly, we started to extend traditional routing designs that are currently focused on routing to destinations consisting of nodes or node aggregations by applying ordering constraints that apply to relations among nodes, such as source-destination pairs.

2.4.1 Spatial Contention Resolution in Wireless Networks

Traditional medium access control (MAC) protocols typically utilize temporal mechanisms for contention resolution, taking the set of competing nodes as a given, and addressing the problem of adapting each node’s channel access probability to the given channel contention level. As reported in the previous annual report, we have explored an alternative approach for wireless networks—named “spatial backoff”—that adapts the “space” occupied by the transmissions. Spatial backoff is implemented by joint adaptation of transmission rate and carrier sense thresholds used by the nodes in the networks. In our recent work on this topic, we have improved on the previous spatial backoff protocol, by incorporating mechanisms that facilitate performance improvements in the presence of channel fading. This approach also determines receiver sensitivity as a function of the channel conditions. Performance improvement in presence of fading, over prior work, is obtained by improving the algorithm for adaptation of carrier sensing and transmission rate, in response to time-varying channel conditions and packet loss patterns.

2.4.2 MPR-based Medium Access Control

We designed and analyzed MAC protocols aimed at enabling collision-free channel access in single-channel and multi-channel networks, as well as the use of virtual MIMO schemes.

We developed a new protocol for collision-free channel access in ad hoc networks called Bid Activation Multiple Access (BAMA) [69]. BAMA is based on bids made by nodes for slots within the context of probabilistic channel access. Winners of the bids for a given slot are determined as a result of a fair election of the bids for that slot. Nodes attempt

to acquire varying number of slots depending on their traffic requirements. Nodes transmit their schedule information once in each frame prior to the data packet transmission in the slots acquired by them. Mismatched schedule information for a given slot are corrected based on the same fair election by the nodes that hear the schedule information. Discrete-event simulations were used to compare BAMA with other MAC protocols, with the results showing that BAMA provides better throughput and much lower end to end delay at low and high traffic loads. The traffic adaptive nature of BAMA allows for the performance of BAMA to be largely independent of the network load.

We applied the same basic approach used in BAMA to take advantage of MIMO nodes. We introduced an Election based Hybrid Channel Access (EHCA) protocol for ad hoc network to achieve high throughput and bounded channel access delay at the same time [70]. EHCA reduces the contentions during the channel scheduling formation through fair node elections, which are based on the topology information. Only the elected nodes contend for the channel and broadcast the scheduling result. We used numerical analysis and simulation experiments to illustrate that EHCA outperforms alternative designs.

Lastly, we propose the distributed CHannel Access scheduling using virtual MIMO Protocol (CHAMP) [71, 72]. In CHAMP, nodes build a channel schedule in a distributed fashion to utilize the spatial multiplexing gain of virtual MIMO links. CHAMP also introduces a cooperative relay strategy to fully utilize the available degrees of freedom of virtual antenna arrays. We analyzed the single-hop saturation throughput of CHAMP and evaluated its multi-hop performance through simulation. The results of our analysis show that CHAMP can achieve better performance than a contention-based MAC protocol using MIMO links.

2.4.3 Multicasting with MIMO

Conventional broadcast (and multicast) suffers of an efficiency issue related to broadcast MAC mode of operation. Namely, if an IEEE 802.11 MAC protocol type is used, a packet is transmitted in broadcast mode, without the benefit of RTS, CTS and ACK. Lack of RTS/CTS implies that hidden terminal conflicts may occur. Moreover, lack of the ACK precludes loss recovery. To reduce hidden terminal conflicts and degradation, a staggered transmission policy is generally enforced. More precisely, when the forwarding node receives a broadcast or multicast packet, it randomly delays its transmission by several packet transmission times. This extra delay, however, causes considerable throughput loss (up to a factor of ten at times). In this research, we propose a new ad hoc multicast protocol, MIMO-CAST [52], that exploit the cross layer interaction between physical, MAC and network layer. MIMO-CAST alleviates the broadcast/multicast MAC inefficiency by using Multiple-Input Multiple-Output (MIMO) selective reception feature and Multi Point Relay forwarding. We investigate the performance improvement of MIMO-CAST through a simulation study.

The MIMO-CAST solution consists of two phases. In phase I, each source selects a set of Multi Point Relay (MPR) neighbors. This is the minimum set of neighbors that can cover with their broadcast all the nodes 2-hops away from the source. The MPR scheme is recursively applied until the MPR nodes form a tree that emanates from the source and covers all nodes. With MPR, only a restricted set of nodes can forward, thus the likelihood of a collision is greatly reduced. The possibility of hidden terminal collision still exists,

however, if a downstream node is exposed to two MPR-type forwarding nodes. This node will receive the broadcast packet twice - from each of the two MPR nodes. To prevent it, the MPR nodes must stagger their transmissions (with consequent loss of throughput). The MIMO radio at the exposed node resolves this problem. Namely, the exposed node computes different sets of weights for its MIMO array. Each set of weights tunes the antenna array to just one MPR transmitter and blocks the duplicate packets from all others. We evaluate the throughput and delivery ratio improvements obtained first with the MPR reduction, and then with MIMO implementation. In random layout scenarios, the throughput gain in MIMO-CAST is up to 10% compared to omni-antenna system with MPR technique and up to 50% compared to ODMRP. In worst case situations, with hand picked topologies that emphasize the hidden terminal problem, MIMO-CAST throughput gain is up to 50% even with respect to the MRP scheme. In all environments, MIMO-CAST packet overhead is lowest of all.

We plan to extend our simulation study of MIMO-CAST to mobile environments. The current MIMO-CAST simulation study does not include mobility model. However, mobile devices with multiple antennas will be supposed to be common in real world due to improvement of vehicular ad hoc networking. Data dissemination and gathering in the VANET can be expedited by MIMO technology. In particular, we will investigate the use of MIMO-CAST for communication between groups of moving vehicles, e.g., police cars, firefighter engines and emergency vehicles.

2.4.4 Mesh-based Multicasting Approaches for MANETs

We have introduced extensions to our recent work on mesh-based multicasting. Mesh-based multicast routing protocols build multiple paths from senders to receivers. Higher redundancy results in higher reliability because packets can be delivered even in the presence of links breaking. However, in less dynamic environments, in which links break less frequently, the additional redundancy may not be needed in terms reliability and may significantly increase overhead.

We investigated [62] the tradeoffs between reliability and efficiency in mesh-based multicast protocols for MANETs. We introduce an adaptive mesh-based multicast mechanism that controls mesh redundancy based on link reliability in the neighborhood of the node. Mesh redundancy is measured by the number of paths from each receiver to the core of the group's mesh, which serves as the address of the group. We introduced a metric called Mesh Reliability Index (MRI), which allows nodes to estimate the reliability of the mesh in their neighborhood, and determine whether redundancy needs to be increased or decreased.

We introduced the adaptive mesh-based multicast routing protocol (ADMP) [63], in which the redundancy of a multicast mesh is modified in response to perceived mobility of nodes.

Capacity improvement is one of the major challenges in the design of mobile ad hoc networks. Use of multiple channels is a useful technique in order to achieve capacity improvement by allowing nodes that need to exchange data to operate on the same channel and nodes that do not need to exchange data to operate on different channels. In the recent past some research has been done in the area of improving channel capacity using multiple

channels for unicast flows. However we are not aware of any prior work for improving the channel capacity for multicast flows. We developed the Cross Layer Ad hoc Multiple channel Multicasting Protocol (CLAMMP) for mobile ad hoc networks [64]. CLAMMP is the first protocol for MANETs which uses multiple channels to increase capacity for multicasting flows. CLAMMP is a cross-layered protocol in the sense that it traverses both the routing as well as the MAC layers. Using simulations in Qualnet 3.5, we compared CLAMMP with PUMA (tree-mode) and ODMRP, which are representatives of mesh-based and tree-based multicast routing in ad hoc networks. The results from a wide range of scenarios show that CLAMMP improves network capacity by an order of magnitude compared to the other two protocols.

2.4.5 Efficient Broadcasting in MANETs

Many signaling or data forwarding operations involve the broadcasting of packets, which incurs considerable collisions in ad hoc networks based on a contention-based channel access protocol. We introduced the *Three-hop Horizon Pruning* (THP) algorithm [65] to compute *two-hop connected dominating set* (TCDS) using only local topology information (i.e., two-hop neighborhood). Because every node has the two-hop neighborhood information, it is possible to maintain fresh routes to all nodes within two hops. In this situation, a TCDS is ideal for the propagation of *route request* (RREQ) messages in the route discovery process of on-demand routing protocols. THP is shown to be more efficient than all prior distributed broadcasting mechanisms, when a TCDS is preferred over a *connected dominating sets* (CDS).

Like all other algorithms that depend on local topology information, THP is not reliable when the topology changes frequently, and there is a clear trade-off between reliability and efficiency. We developed and analyzed two enhancements to THP that address the lack of reliability of neighbor information. First a *virtual radio range* (VR) is used that is shorter than the physical *radio range* (RR). A node considers as one-hop neighbors only those nodes within VR (we do not use two different radio ranges, as in prior work, because it can incur additional interference). The gap between VR and RR works as a buffer zone, in which nodes can move without loss of connectivity. Second, upon receiving a broadcast packet, the forwarder list in the packet header is analyzed together with the current information about the local neighborhood. Based on that, a node may decide to broadcast the packet even though it has not been selected as a forwarder. We conduct extensive simulations and show that AODV-THP with these two enhancements attains better performance than AODV in terms of delivery ratio, control overhead, packet collisions, and end-to-end delay.

We also introduced a clustering technique addressing redundancy for bounded-distance clusters [66], which means being able to determine the minimum number of *cluster-heads* per node, and the maximum distance from nodes to their cluster-heads. This problem is similar to computing a (k, r) -*dominating set*, (k, r) -DS, of the network. (k, r) -DS is defined as the problem of selecting a minimum cardinality vertex set D of the network such that every vertex u not in D is at a distance smaller than or equal to r from at least k vertices in D . In mobile ad hoc networks (MANETs), clusters should be computed distributively, because the topology may change frequently. We developed *the first centralized and distributed solutions* to the (k, r) -DS problem for arbitrary topologies. The centralized algorithm computes a $(k \cdot \ln \Delta)$ -approximation, where Δ is the largest cardinality among all r -hop neighborhoods

in the network. The distributed approach is extended for *clustering* applications, while the centralized is used as a lower bound for comparison purposes. Extensive simulations were used to compare the distributed solution with the centralized one. As a case study, we proposed a novel multi-core multicast protocol that applies the distributed solution for the election of cores. The new protocol was compared against PUMA, which is one of the best performing multicast protocols for MANETS. Simulation results showed that the new protocol outperforms PUMA on the context of static networks.

2.4.6 Applications of Network Coding to Network Control

Distributed Algorithm for Multicasting: While most network coding solutions employ coding at all possible nodes, we have pointed out in [115] that it is often possible to achieve the network coding advantage by coding only at a subset of nodes. Given that performing network coding operations may entail some additional cost either in the application layer or in the buffer management at network nodes, it is of natural interest to find out the nodes where network coding is necessary to satisfy the communication demands.

In particular, if we are given a heterogeneous wireless network where legacy nodes may not do network coding, it is important to understand where the coding nodes need to be placed and how they should interact with other non-coding nodes to obtain as full as possible benefit of network coding.

We have shown in [115] that it is NP-hard to find the minimal number nodes where network coding is required to achieve the multicast capacity. By others [120], even approximating the minimal number of coding nodes within any multiplicative factor or within an additive factor of $|V|^{1-\epsilon}$ has been shown NP-hard by others. Existing approaches employ either greedy algorithms [120, 121] or linear programming formulations with exponentially growing number of variables and constraints [122], both of which are centralized.

For the problem of optimizing the resources engaged in network coding in a generic multicast scenario, we have proposed an evolutionary approach based on a genetic algorithm, demonstrating its benefits over other existing approaches in terms of the solution quality and the applicability to a variety of generalized scenarios [115]. Along the same direction, we have developed a number of novel mechanisms which greatly improve the algorithm's performance and practicability [116, 117, 118, 119]:

- We have presented in [116, 117] a block-wise genotype encoding method with the associated genetic operators which, by preserving the inherent modularity between the variables given by the network topology, leads to far superior solutions than the original algorithm in [115].
- We have developed a novel distributed framework of the algorithm [117], where the resource optimization can be done on the fly integrated into a decentralized network coding framework with a much lower complexity. We also have proved in [117] that despite its stochastic nature, our proposed algorithm provides the worst-case performance bound at least as good as the existing algorithms [120, 121].
- In [118], we have further improved the performance of the algorithm by distributing

the management of the population (i.e., the set of candidate solutions) along the temporal axis such that a number of sub-populations are managed by successive packet transmissions over the network.

- We have proposed in [119] a distributed evolutionary algorithm that may reveal the utility of network coding in comparison with the amount of saved link cost, which can be used to make decisions on the deployment of the network coding capability such that coding happens only at the places where significant amount of link cost is saved.

An immediate extension is to apply our proposed evolutionary algorithm to the multicast scenario over the aforementioned heterogeneous wireless networks. Provided that the existing nodes are programmable, we can run our distributed algorithm directly over the network, during which each node performs coding operations temporarily on the application layer to find out the set of the nodes where deploying the network coding capability is found advantageous. It is worth to point out that at the end of the iteration, our algorithm produces not only the set of the coding nodes, but also the relevant network code at each coding node. If, on the other hand, the legacy nodes are not able to perform any operation beyond the traditional routing, we may add a number of “smart” nodes to the existing network such that each legacy node is reachable from a smart node within a few hops. We may then apply a modified form of our evolutionary algorithm where coding operations at the legacy nodes are simulated by the added smart nodes during the iteration of the algorithm.

Ongoing research topics include investigating the applicability of the algorithm when delays, failures, or topological changes in the network are taken into account, which are unavoidable in wireless networks. Also, we may further generalize the evolutionary algorithm to construct a random network code for the much harder case of non-multicast scenario in a reliable manner.

Using Network Coding to Improve The Link and Transport-Layers: The Recent work on the application of network coding to wireless environments, for both multicast and unicast, has assumed that each individual broadcast transmission (of an encoded packet) occurs at a fixed, lowest-possible rate. Such approaches fail to exploit an additional degree of freedom available in wireless environments, namely link-layer rate diversity, whereby individual nodes can transmit at faster rates at the expense of corresponding smaller coverage area. Recent work has demonstrated that effective exploitation of such rate diversity by routing algorithms can result in dramatic increases in the achievable throughput. We have developed a few examples that demonstrate how combining rate-diversity with network coding can provide a larger capacity again for data dissemination of a single multicast flow [49]. We investigated these properties through extensive simulation in Qualnet; more precisely, we compared the performance of network coding in combination with transmission rate diversity, for a realistic stream-oriented application.

In addition, we have explored PiggyCode [50], a network coding based scheme specifically designed to enhance TCP performance over IEEE 802.11 multi-hop wireless networks. The root of this approach is a network coding module operating between the Network and the MAC layer. Each node running PiggyCode combines and encodes, whenever, TCP-DATA and TCP-ACK packets belonging to the same information flow. The coding approach is

conceptually analogous to piggybacking the TCP ACK packet within the TCP-DATA packet, with the substantial difference that, by performing network coding operations: (1) we can piggyback at the network layer (whereas conventional ACK piggybacking is possible only at the transport layer and thus rarely used since TCP flows are generally unidirectional), and; (2) the actual packet size remains unchanged. The proposed scheme is simple and effective. It reduces the overall number of transmissions on the channel leading to throughput gains up to 16% and more importantly reducing end to end delays.

In the interaction between network coding and link rate diversity, we plan to study the sensitivity of the results to the specific rate-range curves used to characterize rate diversity. Our results provide preliminary evidence that wireless network coding may lead to a latency-vs-throughput tradeoff. Also, we plan to work on PiggyCode extensions where we consider the presence of multiple competing flows, and we explore potential additional benefits as well as fairness implications.

2.4.7 Routing Protocols for Disruption-Tolerant Networks

A fundamental assumption on which the architects of the IP Internet and wireless multi-hop ad hoc networks (MANETs) have based the design of their routing protocols is that physical connectivity exists on an end-to-end basis between sources and destinations for extended periods of time, and that in the worst case, network disconnections are infrequent and short-lived. This assumption has had profound implications on how communication bandwidth is shared, how routing is accomplished, and how data is disseminated. In particular, routing in packet-switching networks has been based on routing tables derived entirely from topology (or connectivity) information that represents only a snapshot of the state and characteristics of network links at particular instants.

While the end-to-end connectivity assumption is justified in wired networks, the cost, energy consumption, and form factors of computing devices have enabled embedded computing and networking devices that can be used in environments in which end-to-end connectivity may be intermittent at best. These new application environments range from interplanetary research [91] to wearable computers [92]. Example applications include monitoring of wild life and disruptive phenomena (e.g., wild fires), object tracking, emergency response, vehicular or interpersonal networking, and the tactical communication in the battlefield.

Networks in which end-to-end connectivity is not guaranteed have been called delay-tolerant, disruption-tolerant, intermittently-connected, episodically-connected, or highly-partitioned. In this paper, we use the term *disruption-tolerant networks*, or DTNs. Clearly, routing in a DTN cannot be accomplished in the same way as routing in a network in which end-to-end connectivity is assumed to exist except for extraordinary circumstances. As the seminal work by Fall [95] and others has shown, routing in a DTN must be accomplished differently than in traditional networks. Routing in the Internet and well-connected ad hoc networks has no temporal dimension, because it is based on a distributed or local search of paths obtained from snapshots of the network topology. In contrast, routing in a DTN must be a function of space and time, because physical links exist only temporarily, and paths from sources to destinations can be considered to exist only as functions of connectivity (links) occurring over time.

Starting with the work of the Interplanetary Internet Research Group (IPNRG) [93] within the IRTF (Internet Research Task Force), considerable effort has been recently devoted to the study of networks with intermittent connectivity or very long latencies. A notable example is the work by the DTNRG (Delay Tolerant Networking Research Group) [94] initiated in 2002 under the IRTF. Our review of prior work on DTNs indicates that prior solutions to the routing problem for DTNs rely on knowing the entire network topology, or the ability to control some nodes, or the ability to duplicate data freely in the network.

In this part of our work in the DAWN project, we introduced a routing framework for DTNs designed to work as efficiently as existing approaches for routing in ad hoc networks when the network is connected, and to render the same data delivery results of epidemic routing but with only a fraction of the overhead incurred per packet delivered. We extend the notion of on-demand routing to accommodate disruptions in network connectivity of arbitrary duration, and, in doing so, make two notable contributions:

- We propose an approach to establish and maintain loop-free routes in both connected networks and in DTNs, without assuming any a priori knowledge of node schedules or location, but leveraging past connectivity history to predict future routes.
- We introduce a set of techniques for limiting the temporal and spatial scope of control information dissemination.

We call our routing framework for DTNs Steward-Assisted Routing (StAR). StAR uses *steward* nodes to deliver data to destinations on behalf of the sources. A steward can be the destination itself (if there exists a direct route connecting source and destination), or another node deemed likely to have a path to the destination in the future. StAR ensures that forward paths are preserved toward destinations of current interest. StAR minimizes the amount of routing information disseminated throughout the network. It ensures that only those nodes who may at some point be elected as a steward for a destination maintain related routing information. Just as on-demand routing limits routing table entries to those nodes on a direct path between source and destination, StAR limits routing table entries to only those nodes who are likely to be on a path between source and destination at some point in the future. Our framework does not require a priori knowledge of node schedules, time synchronization among nodes, location information (e.g., from GPS). Routes are established based purely on contact histories, i.e., information on recent connectivity. The results from simulation experiments illustrate that StAR performs as efficiently as traditional proactive or on-demand routing schemes when the network is connected, and provides data delivery comparable to that of epidemic routing in DTNs, but incurs only a fraction of the overhead.

A paper describing part of our work on routing in DTNs received the Best Paper Award at the IFIP Networking 2007 Conference in Atlanta, GA [96].

We have also proposed *utility-based replication* [97] as an efficient opportunistic routing mechanism in networks with heterogeneous node populations. We show that our utility-based routing approach can improve delay and delivery ratio when compared to existing, greedy-based replication solutions 4-5 times. We also introduced a general analytical framework based on fluid models that can be used to analyze the delay of opportunistic routing solutions in networks with different classes of nodes.

2.4.8 New Routing Frameworks in MANETs

In the past, routing protocols have been developed following a vertical approach, i.e., each protocol is built with its own mechanisms, which are not shared with other protocols. For example, unicast routing protocols for ad hoc networks (e.g., DSR [74], AODV [76], OLSR [73], TBRPF [75] and the like) operate independently of multicast routing protocols (e.g., MAODV [79], CAMP [77], ODMRP [78]).

Another aspect of routing in MANETs has focused on avoiding multiple access interference (MAI). Accordingly, they tend to maintain single paths to destinations, data packets are disseminated using single-copy forwarding, and protocol signaling attempts to minimize the number of nodes that forward information and MAI. Examples of techniques used to reduce MAI in routing and forwarding include introducing jitter in the transmission of periodic updates, using multiple node-disjoint paths to reach destinations, using multicast trees, and using multi-point relays to disseminate link states.

The basic routing schemes can be classified as proactive and on-demand. In the basic proactive routing scheme, either link-state or distance updates propagate throughout the network for nodes to update their routing-table entries for all destinations. In on-demand routing schemes, route requests are disseminated throughout the network to find destinations of interest. In large MANETs. The frequent propagation of signaling packets throughout the entire network to update routing tables is a detriment to network performance.

This part of our research in DAWN focuses on investigating a new theory of routing applicable to MANETs. A key motivation of our work are our recent results on the capacity of wireless networks in the presence of multi-packet reception (MPR). Routing and forwarding in the context of many-to-many communication call for the exploitation of concurrency at the link level and redundancy at the network level, because the MAI caused by data and control packets can be managed and exploited. Hence, a route to a destination should be a “multipath” consisting of multiple paths that need not be edge or node disjoint, multi-copy forwarding can be used to disseminate data over a multipath, periodic updates should be sent so that multiple concurrent updates reach the neighbors of transmitters at the same time, multicasting can be attained over “concurrency” meshes in which all multicast transmissions are useful information, and “feasible concurrency relays” can replace today’s multi-point relays to disseminate control signaling in a way that a relay is feasible if it can transmit concurrently with other nodes to intended neighbors.

During the past year, we have investigated two aspects of a new theory for routing in MANETs: (a) reducing signaling overhead, and (b) integrating routing with scheduling in the context of many-to-many communication.

Reducing Signaling Overhead: Several approaches have been proposed to reduce the communication overhead incurred in updating routing tables. These approaches include organizing the network into clusters, reducing the rate at which signaling packets propagate away from the origin of an update, and using geo-location information to direct signaling packets to particular regions of the network.

Examples of cluster-based routing date back to the DARPA packet radio network (PR-NET). Starting with the hierarchical routing scheme proposed by Kleinrock and Kamoun [80],

many other schemes have been proposed for proactive hierarchical routing using distance or link-state information. The Zone Routing Protocol (ZRP) [81] is an example of hierarchical routing that combines on-demand routing done between clusters and proactive routing done within clusters. The limitation of cluster-based schemes is the need to re-affiliate nodes to clusters when nodes leave their current home clusters.

Examples of schemes that reduce the rate at which signaling is propagated away from destinations also date back to time PRNET times. Recent approaches include expanded-ring search optimizations used in on-demand routing protocols. Another example is the fisheye state routing [82] scheme. The directed flooding based routing [83] and Gradient Based routing schemes (GRAB) [84] involve establishing different policies for flooding. The OPRAH protocol [85] uses an opportunistic routing scheme that exploits promiscuous listening by the radios to cache route information and impose constraints on the forwarding of this information within a given threshold. The limitation with threshold-control schemes is that they may not provide enough accuracy when sources and destinations are far away, and information about destinations or links propagates in all directions, not just towards those nodes that need the information.

The location aided routing (LAR) [86] scheme is a well-known approach based on location information to direct the transmission of route requests. The advantage of LAR is that signaling is confined along areas where destinations were located. The limitation of LAR and other location-based schemes is the need to use techniques such as GPS for the localization of nodes.

Our work over the past year has two motivating factors. First, a number of protocols have shown important performance gains by the use of location-information (e.g., LAR) or threshold-based approaches (e.g., OPRAH). Second, our own work on the capacity of wireless networks clearly shows that the signaling of routing protocols should be interest-driven. From the brief summary of prior work we just presented, it is clear that all routing schemes focus on maintaining routing entries to destinations. In this project, we have focused on changing the way routing is done in a MANET by investigating routing schemes that maintain information regarding source-destination pair, in order to reflect the interest of some nodes in other nodes more explicitly in the signaling.

We have developed the Elliptic Demarcation of Information Transfer (EDIT) approach to routing in MANETs. EDIT consists of maintaining routing-table entries for source-destination pairs in a way that the dissemination of signaling packets is confined as much as possible within regions of interest defined in a distributed manner by the distance that the node hosting the entry has to both the source and destination of a given route. Unlike prior threshold schemes, a region of interest in EDIT is inherently an elliptical zone with a source and a destination as the foci of the ellipse, rather than a ring-shaped zone as in prior threshold-based schemes based solely on distances away from destinations or sources of updates.

In EDIT, regions of interest are defined on the basis of source-destination pairs, rather than on the basis of destinations alone. A node within the region of interest of a source-destination pair must forward signaling packets for the pair, and nodes just outside the region are allowed to not forward the signaling packets for the pair. A source s and a destination d form the two foci of an ellipse defining the region of interest for the routing information

pertaining to the path from s to d , and a node decides whether or not it belongs to the region of interest for the pair based on the relationship between the length of the known route from s to d and the distance from the node to s and to d .

The underlying protocol to which EDIT we apply EDIT is the Destination-controlled Source-sequenced Labelled Routing protocol (DSLRL) [87]. DSLRL uses route requests (RREQ) and route replies (RREP) as its basic signaling units. A RREQ is sent by a source seeking a destination or is forwarded by a relay node, while the RREP is sent by the destination or a relay upon receipt of a RREQ for which a valid route is known. A RREQ specifies, at a minimum, a *source sequenced label (SSL)*, a *relay sequenced label (RSL)*, and a destination identifier. The SSL uniquely identifies the request by the identifier of the source originating the RREQ and a sequence number generated by the source. The propagation of a RREQ results in a directed acyclic graph (DAG) rooted at the source and identified by the SSL and the destination identifier. The RSL is significant only in the neighborhood of the node sending the RREQ, and it equals the value of the SSL of the node forwarding the RREQ. RREPs contain, at a minimum, An SSL, and RSL, the destination identifier, and a distance to the destination. Node r accepts a RREP in response to a RREQ it originates or relay regarding destination d only if the RREP specifies the SSL and RSL that r used in its last RREQ for d .

We carried out simulation experiments using the Qualnet simulator. EDIT was implemented starting with the code written originally for the loop-free routing protocol described in [87] as the underlying unicast routing scheme. The scenarios typically include 100 nodes with 2 separate scenarios containing 10% and 30% active flows, ie., distinct SD pair flow. The simulations run for a duration of 900 seconds and the average duration of each of the flow is less than third of the simulation time. The simulations were run with 10 random seeds to ensure that the results are not an artifact of the scenario. Each of the flows is a randomly selected constant bit rate (CBR) application generating 1 packet per second with 1000 packets sent for each flow. The area of the network is a 1500m X 1500m region with nodes randomly placed across it. Node mobility is configured using the 'Random Waypoint' mobility model in which a node selects a point randomly and moves towards it at a uniformly distributed speed ranging from 1 to 10 m/s.

From the results obtained in our simulation experiments, is clear that EDIT substantially outperforms AODV and OLSR, and it also outperforms DSLRL, which is the underlying loop-free method used for EDIT. This indicates that the use of regions of interest helps the performance of EDIT. The simulation results also show that EDIT performs comparatively much better in conditions of high mobility. EDIT-GPS performs slightly better than EDIT, because of the intrinsic scoping combined with the prediction scheme. However it must be noted that EDIT without GPS data still performs quite close to EDIT-GPS and LAR, except for latency, where it takes longer to deliver packets than the GPS-based routing.

The results of this work have been submitted for publication. Our next steps include extending the notion of source-destination pairs to relations, i.e., routing to relations of nodes rather than simply destinations, using lexicographic orderings of relations. We also plan to apply our approach to routing by names, rather than node addresses.

Integration of MAC and Routing: We believe that embedding the signaling needed to establish multipath routing with the signaling needed to establish transmission schedules is the main routing challenge for many-to-many communication. Important problems associated with this challenge are: (a) How should nodes elect and reserve time slots for the signaling required for unicasting and multicasting that exploit concurrency and redundancy? (b) How should feasible concurrency relays be selected to maximize the reliability of signaling while making efficient use of link-level concurrency? (c) How should the “width” of the multipaths (number of neighbors each node uses as next hops to a destination) be controlled depending on demand? (d) How should reliability be increased or average delay or jitter be decreased by means of multi-copy forwarding over multipaths? and (e) How should MPR and NC be combined in the context of scheduled multipaths for the dissemination of data and control information?

Over the past year, we have concentrated on multi-channel multi-radio (MCMR) systems, which are being introduced to exploit the frequency diversity of the wireless networks. By assigning the interference links with orthogonal channels, a MCMR system can dramatically reduce the wireless interference that widely exists in the classical multi-hop wireless networks and enhance the network capacity. In MCMR networks, channel assignment, routing and scheduling are dependent on each other. The input of any component is partially decided by the output of the other two components:

- **Transmission scheduling:** channel assignment decides whether two links are interfere with each other, and route selection decides which links will be used for transmissions.
- **Channel assignment:** different transmission scheduling will generate different interference link set, it further decides which links need to be assigned with orthogonal channels; good route selection balance the traffic throughout the network so that the channel diversity can be utilized to the largest extent.
- **Route selection:** channel assignment decides the network topology, which influences the route selection results directly; since routing control packets are transmitted as the data packets at the MAC layer, the transmission scheduling decides how the routing information is propagated throughout the network.

However, the correlations between these three components are at different timescales. We note that channel assignment and scheduling are formed based on the two-hop information, while route selection are made based on the end-to-end information between the traffic source and destination. So channel assignment and scheduling are coupled with each other more tightly at small timescales (a few packet transmissions), while route selection interacts with the other two components at large timescales (hundreds of packet transmissions). To fully leverage the spatial and frequency diversity of MCMR networks, we need to jointly consider the channel assignment, routing and scheduling problem. There are several challenges in designing a fully distributed joint channel assignment, routing and scheduling algorithm. First, how to evaluate a transmission schedule is efficient in terms of both channel diversity and spatial reuse. Second, how MAC layer and network layer interact correctly to exploit the frequency diversity and spatial reuse at both layer.

Accordingly, we have started to investigate distributed **J**oint channel **A**ssignment, **R**outing and **S**cheduling protocols for wireless mesh networks (JARS). Due to different characteristics of broadcast and unicast transmissions, JARS must adapt different channel-assignment and link-scheduling strategies according to packet types. For broadcast transmissions, JARS requires all nodes in the communication range to converge on a common channel at the same time slot, which allows the broadcast transmission propagate throughout the network through the efficient utilization of the broadcast nature of wireless medium. For unicast transmissions, we introduce a unified metric, *transmission fraction*, to evaluate the efficiency of the joint channel assignment and link scheduling in terms of spatial and frequency reuse. The transmission fraction is used to replace the traditional link cost in the route distance calculation. We plan to submit the results of our research for publication later this year.

2.5 Task 4: Energy-Efficient Networks

In this task of DAWN, we have investigated the use of the SINR model in channel access, the use of multiple control knobs to increase the attainable maximum throughput in a network, schedule-based channel access aimed at reducing energy consumption, and completed our work on energy-consumption models for energy constrained networks.

2.5.1 Using the SINR Model for Power and Rate Control in Channel Access

A fundamental problem for media access control (MAC) in ad hoc networks is whether to use scheduled transmissions, that is transmissions over orthogonal channels (simplest version of which is exemplified through TDMA) versus contention-based transmission. In traditional analyses, the networking viewpoint has been that simultaneous, non-orthogonal transmissions result in destructive collisions. Based on that simplistic model and on the equally, if not more, simplistic assumption of a sharp cut-off in the transmission/interference range based on distance, the trade-offs and comparison for the two classes of MAC protocols have been well understood and, in fact, have formed the basis for standard protocols, like the ones in the 802.11 suite. However, such protocols have showed intrinsic shortcomings and deficiencies when applied to multi-hop ad hoc networks and the reason is precisely the simplistic model of the physical layer. A great deal of work has been done to modify the logic of these protocols but almost invariably the improvements have been limited because again the physical layer is not adequately modeled. In our work we chose to use the SINR criterion (Signal-to-Interference-plus-Noise Ratio) because it is a good compromise between the traditional "disk" models and the full-fledged Information-theoretic work (which, in addition to its complexity, suffers from the inability to capture the notion of delay). The SINR criterion simply requires that its value at the receiver exceeds a certain threshold for the transmission to be successful. This model implicitly assumes that the combined effect of interference is closely approximated by that of additive Gaussian noise. Clearly, the choice of the threshold reflects a variety of physical layer parameters including the form of detector (matched filter, multi-user-optimal or sub-optimal), the modulation and coding scheme, the target quality-of-service expressed in terms of bit-error-rate (BER), and, most importantly, the transmission rate. The lower the rate, the lower the value of the threshold needs to

be. By contrast, the lower the value of the BER, the higher the value of the threshold. Thus, the transmission power, the transmission rate, and the BER are all intricately related and their analytical relationship is known for simple uncoded modulation schemes or can be approximated and computed.

It is clear, therefore, that power control and rate control are two important control levers that can affect throughput. Connecting to the observation that there is also a fundamental distinction between scheduled transmission and simultaneous transmission, we should observe that (i) a minimal level of scheduled access is unavoidable since, at least, nodes in each slot must be separated into transmitters and receivers. It is impossible to transmit and receive at the same time over the same channel with a single transceiver. But apart from that there is still the question whether it is preferable to time-multiplex the users or allow them to transmit simultaneously. The trade-off is understood best if we consider the simple case of M pairs of communicating nodes with designated transmitters and receivers in unicast mode. One alternative is for all pairs to transmit simultaneously. Then by the SINR criterion the denominators in the SINR expressions will be large and the threshold values will have to be lowered for successful communication at the designated BER level. Thus the transmission rates will have to be reduced. Alternatively, the users could be split into two sets of communicating pairs ($M/2$ pairs in each set). Clearly by virtue of time-multiplexing among the two groups, whatever rate is achievable for each will be reduced by a factor of two to reflect the TDMA mode into which the two groups will be forced to operate. However, because the number of competitors is now drastically reduced, the value of the threshold for successful capture will increase. Hence the achievable rate will increase. It is not a priori clear which of the two alternatives yields a better set of rates. And, of course, there are even more choices since the M pairs can be grouped in a variety of different ways. This is the problem that we have started pursuing and continue to pursue. We have already quantified this trade-off and the two attached reports summarize the findings so far. Note that part of this work has leveraged the cooperation of MURI investigators with NRL personnel.

2.5.2 Exploiting Multiple Control Knobs to Improve Capacity

There are several *control knobs* that one can explore to control the sharing range of the wireless medium (and ultimately the degree of spatial reuse): the *transmit power* and *carrier sense threshold* each node uses, the *spatio-temporal domain* in which a node transmits, and the *channel* on which a node transmits. (Note that the carrier sense threshold specifies the received signal strength above which a node determines that the medium is busy and will not attempt for transmission.) While several researchers have explored the use of multi-radios and multi-channels to improve network capacity, the first three control knobs have not been explored. Both the transmit power and carrier sense threshold ultimately determine how many connections can simultaneously take place without significant interference, while the third control knob takes advantage of the spatial and temporal diversity to mitigate the adverse effect of interference.

The importance of spatial reuse in wireless ad-hoc networks has been long recognized as a key to improving the network capacity. One can increase the level of spatial reuse by either reducing the transmit power or increasing the carrier sense threshold (thereby reducing the carrier sense range). On the other hand, as the transmit power decreases or the carrier

sense threshold increases, the SINR decreases as a result of the smaller received signal or the increased interference level. Consequently, the data rate sustained by each transmission may decrease. This leads naturally to the following questions:

- How can the trade-off between the increased level of spatial reuse and the decreased data rate each node can sustain (because of the decrease in the SINR) be quantified?
- Is there an optimal range of transmit power/carrier sense threshold in which the network capacity is maximized?
- What is the relation between the transmit power and the carrier sense threshold?
- Does increasing the transmit power have the same effect of increasing the carrier sense threshold?

We have attempted to answer the above questions in an analytical framework. Specifically, we have carried out the following four activities.

We have derived an analytical model that expresses the network capacity as a function of the transmit power P_{tx} and the carrier sense threshold T_{cs} , under the assumptions that the network is densely populated (so as to consider the worst-case interference scenario) and wireless nodes are uniformly and independently distributed in a region U :

$$\Gamma_n = C_0 \cdot \left(\frac{T_{cs}}{P_{tx}} \right)^{\frac{2}{\theta}} \cdot \log_2 \left(1 + f \left(C_1 \cdot \left(\frac{P_{tx}}{T_{cs}} \right)^{\frac{1}{\theta}} \right) \right), \quad (2)$$

where $C_0 \triangleq \frac{2\sqrt{3} \cdot W \cdot U}{3}$ and $C_1 \triangleq \frac{1}{R}$ are constants, and W is the channel bandwidth in hertz. Note that for ease of analysis, the Shannon capacity under the Additive White Gaussian Noise (AWGN) channel model is used to characterize the relation between the channel rate and the SINR.

While the analytical model assumes that the achievable channel rate is a continuous function of SINR (with the use of the Shannon capacity), there are only a number of data rates available in reality. Ideally given the SINR, a wireless node chooses the maximal data rate that can be sustained. We show that, *under the case of a discrete number of channel rates*, tuning the transmit power offers several advantages that tuning the carrier sense threshold cannot offer, *provided that there is a sufficient number of power levels available*. (The interested reader is referred to [99] for a detailed account.) We also analyze the number of power levels required to achieve the same control granularity as afforded by tuning the carrier sense threshold, and show a number of 5 power levels is sufficient.

We have modeled the channel activities governed by IEEE 802.11 DCF in multi-hop wireless networks by extending Bianchi's and Kumar's models. In a multi-hop wireless network, it is difficult to obtain a consistent view for the entire network — a node may detect the channel to be busy while another node senses the channel to be idle. As a result, we model the channel activities from the perspective of an individual sender, and categorize them as perceived by each sender into four types: *idle*, *busy*, *collision* and *successful transmission*. The effect of accumulated interference is also faithfully incorporated in the model. We

obtain the throughput attained by each sender by deriving the probability that each activity occurs and its expected duration. Based on the analytical model derived, we have been able to identify a simple operating condition under which the network may attain the system throughput that is close to its optimal value (and based on which a distributed algorithm can be readily designed). Specifically, we find that high system throughput can be achieved when the area, SL_s , silenced by a sender s is reduced as much as possible *under the premise that SL_s covers the interference area IN_r of its intended receiver r* . This increases spatial reuse while not deteriorating collisions due to the hidden node problem.

Based on the above findings, we devised a *localized* power and rate control algorithm, called *PRC*, that enables each transmitter to adapt to the interference level that it perceives and determines its transmit power and data rate [107]. The transmit power is determined in a way that the transmitter can sustain the highest possible data rate, while keeping the adverse interference effect on the other neighboring concurrent transmissions minimal.

2.5.3 Energy-Efficient Channel Access

During this past period of performance, we completed the development of the first schedule-based, multi-channel, adaptive medium access framework for multi-hop wireless ad-hoc networks that is highly efficient both in terms of energy consumption as well as network utilization. The proposed channel access framework, DYNAMMA, can also accommodate different traffic adaptation strategies, including explicit traffic announcements as well as implicit techniques (e.g., learning algorithms). Besides testing and evaluating DYNAMMA using the WiMedia PHY under the QualNet network simulator, we have also ported and experimented with an instantiation of DYNAMMA on a testbed consisting of UWB radios manufactured by Realtek.

A paper describing this work [98] received a Best Paper Award at the IEEE MASS 2007 conference. Additional information regarding the technology transfer related to this part of our work is discussed in Section 3.

2.6 Task 5: Large, High-Fidelity Simulations and Testing

Our work in this task of DAWN has focused on techniques that improve the modeling and simulation of large-scale heterogeneous wireless networks. In this report, we summarize four activities that have yielded significant results. The first activity [37] proposes an evaluation framework for vehicular networks to achieve accurate, scalable, flexible and repeatable performance studies through the utilization of a hybrid emulation testbed and incorporation of high fidelity protocol and environment models. The proposed framework not only addresses the unique challenges of vehicular networks but also enables new types of network analyses via the capability of conducting application-centric evaluation. Compared to traditional network-centric evaluation, case studies show scenarios where network-level statistics do not clearly discriminate between the two routing protocols while significant performance differences were observed using the application-level metrics. In particular, we used the preceding framework to study connectivity benefits of using a multihop relaying strategy for improved Internet access in a WiFi-based vehicular environment relative to the common strategy that

allows only direct communication between vehicles and access points (APs) [38]. We use real AP location data and realistic and detailed vehicular mobility traces for our study. Our results show that multihop relaying strategy leads to substantial gains in connectivity relative to direct access as much as 400%, and that multihop relaying combined with increased communication range provides even greater gains (up to 467%). Further, relay paths with few hops are sufficient to realize most of the gain with multihop relaying.

The second activity expanded our work in environmental mobility to present a systematic study to analyze the effect of environmental mobility on wireless link behavior and protocol performance using measurement, analysis, and simulations [39]. Measurement data from channel traces was collected to isolate and quantify the effects of environmental mobility on the channel performance. Efficient models were developed to explain the observed behavior and integrated with network simulation to enable protocol level analysis under such dynamics. We found that the class of protocols that maintain state or have memory but are otherwise agnostic of the channel operations fare poorly by acquiring incorrect information about the channel and are not able to adequately exploit durations where channel conditions are good. Two specific case studies were used to quantify such behavior to show that protocol perform maybe as much as 20% below their expected performance. To remedy this situation we developed a cross layer optimization scheme, called Recovery from Earlier Good State (REGS) that allows protocols to become aware of the underlying channel operations and improve performance by up to 100%.

The third significant development was leveraging the power of advanced Graphical Processing Units (GPUs) to improve the fidelity and runtime of simulations of wireless network that use adaptive antennas.

The fourth activity consisted of the development of a transparent device driver (TDD), which enables the control of several PHY and MAC parameters and the implementation of MAC functionality beyond that allowed by the IEEE 802.11 implementations.

2.6.1 High-Fidelity Application-Centric Evaluation Framework for Vehicular Networks

Vehicular Networks have traditionally been evaluated in the past through **measurement** and **simulation** studies. Small-scale physical testbeds have been used to perform diverse measurement studies that examine the wireless communication characteristics of packet transmission between vehicles and the roadside Access Points (APs). While permitting real implementations to be tested, these are fraught with characteristic drawbacks of physical testbeds such as lack of repeatability, large costs involved, scalability issues, and other issues.

Simulation studies, on the other hand, have been used extensively to investigate vehicular network protocol performance, mainly those running at the Network and MAC layer. While being flexible, cheaper and scalable, simulation models make a lot of abstractions that compromise the accuracy of the results. Importantly, Operational software (e.g. real application implementations) cannot be executed.

The inability of either paradigm to completely resolve all vehicular network evaluation issues necessitates an evaluation framework that leverages the benefits of both physical

testbeds and simulation. Towards this, we use the TWINE hybrid emulation testbed [40] developed at our Mobile Systems Lab at UCLA, that provides an integrated testbed for wireless network evaluation using physical networks along with simulation and emulation techniques, to evaluate large-scale vehicular networks in a lab environment. We have further incorporated vehicular network-specific high-fidelity models of lower protocol layers and physical environments into the framework, to make the results more realistic and to support diverse network conditions. Apart from providing scalability and improved accuracy, it enables application-centric evaluation evaluating vehicular networks from the application level, which provides an insight to the experience of the end-user.

Our novel approach supports the evaluation of real applications in a simulated vehicular network context, using objective application-level metrics that capture the overall user performance vis-a-vis traditional network layer metrics like packet delivery ratio, aggregate throughput, jitter etc., which are agnostic of upper layer applications. The evaluation used a realistic vehicular network environment by integrating high-fidelity mobility traces and real deployment data.

In order to assess application-level metrics, a client or end-host is emulated such that it can communicate with other hosts in the network through an emulated network interface. Simulation is used to model the rest of the vehicular network that doesn't require modeling at such a high fidelity. High-fidelity channel and host models are integrated as well to create realistic environment settings.

We propose the use of the Peak-Signal-to-Noise-Ratio (PSNR) as the application-level objective metric for streaming video, which is highly correlated with the subjective discernment of humans. PSNR is defined as the ratio of maximum possible power of a video signal and the power of corrupting noise that affects the fidelity of the signals representation in the received video. We calculate PSNR by decomposing the sent and received video clips into a sequence of video frames, and compute the image distance between the corresponding frames in PSNR. We have also considered other application-level metrics such as root mean square of error, corrupted frames, number of corrupted intervals, average duration of corrupted intervals, corrupted sec per minute of video and the number of dropped frames.

We performed several case studies that demonstrate the utility and benefits of an application-centric evaluation paradigm. We considered vehicles moving on a freeway forming a VANET connected to roadside APs that serve as Internet Gateways. We consider a video-streaming application run at one of the clients. Two popular ad hoc routing protocols with different approaches, AODV and GPSR, were considered. 802.11b was used for the MAC and PHY maintaining a fixed transmission rate of 11Mbps. Channel effects were modeled using the 2-ray pathloss model and a Rayleigh fading model with varied maximum fading velocity was used.

By varying the wireless channel quality and the vehicle density we were able to show the impact of the vehicular network environment on the PSNR, i.e. application-level performance. Our results show that the nature and extent of the impact of application-level performance also depends on the underlying routing protocol. Also, the impact of a particular protocol (network layer), on the application-level performance differs depending on the choice of a protocol at other layers (e.g. MAC). Using this application-centric evaluation framework, we can thus evaluate application design and implementation in a target VANET,

instead of as a stand-alone process.

We can also study the correlation between application-level and network-level performance metrics. We have found through our case study that application-level metrics are more directly related to end-user experience and often the network-level performance metrics cannot capture this. Depending on the application, it could be complicated to identify the appropriate set of network-level metrics that closely reflect the performance at the application layer, implying that a new set of metrics would have to be devised to effectively study the impact of network operation on end-user experience.

To produce close-to-reality vehicular movement patterns, we aim at integrating vehicular traffic simulators such as CORSIM and TRANSIMS into our network simulator QualNet. Currently, we have successfully incorporated vehicle mobility traces obtained from a detailed vehicular movement simulation over real road maps using MMTS.

2.6.2 Performance Implication of Environment Mobility in Wireless Networks

Environment Mobility refers to the ambient motion of people, vehicles and other objects in the vicinity of wireless communication, in contrast to nodal mobility that accounts only for the effects of movement of the transmitting or receiving nodes. We have built on our previous work on environmental mobility and characterized the impact of environment mobility on the operation of a wireless network and proposed ways to mitigate their impact. In this work, we have performed a systematic study to analyze the effect of environmental mobility on wireless link behavior and protocol performance using measurement, analysis, and simulations.

By collecting 60 hours of channel traces over a period of two months at different times of the day, we were able to capture the varying magnitude of environmental mobility in a typical university campus, corresponding to mobility patterns like no mobility, far mobility (no mobility allowed within 10 metres of the radios), and unrestricted mobility. We observed that the channel is affected by fixed scatterers, that cause the well-known multi-path fast fading effect, and the movement of people and other obstacles. When the effect of mobile people is significant, we observe a super positioning of this shadowing over the fast fading caused by the fixed scatterers. In particular, we study the impact of Environment Mobility on the network performance. We have explained the blocking of rays by the obstacles by the phenomenon of diffraction and proposed the use of a three-knife edge diffraction model to represent this effect, and validated the model with the measured data. The channel fading under the movement of multiple people is modeled as a two-state Markov Process model that captures that alternating channel quality between the “good” and “bad” states. The transition between these two states is governed by the dynamics of mobility of the people including factors such as the density of people, their speed of movement, and the separation distance of transmitter and receiver on the transition rates between good and bad states.

Information theoretic analysis of the EM channel suggests that such a channel is more correlated or has more “memory” as compared to a multi-path fast fading channel with similar bit-error rates. As a result, the effect of environment mobility is manifested differently in the higher layer protocols than that of the fast fading channel, illustrated through two case studies.

The switching between good and a shadowed state could have an unfavorable effect on

protocols that maintain state via feedback from the channel but are otherwise agnostic of the underlying operations. While protocols that learn dynamically about current link conditions and modify their states and operations accordingly are quick to learn the bad information, they are slow to discard it as the conditions improve. In an EM channel, the link can switch to a good state while the protocol is still operating under the assumption of the bad state recorded in the recent past. Thus, they are not able to adequately utilize the durations when the channel conditions are good, thereby leading to underachievement of expected performance. However, as the changes are a lot slower in traditional fast fading channels, the protocol performance improves.

By studying the interaction of a popular data rate adaptation algorithm *SampleRate* with the EM channel model, we again observe that protocols that maintain state can acquire negative information in a bad state that may be discarded slowly or not discarded when the channel conditions improve. Thus, the protocols are not able to capitalize on the durations where channel conditions are good, adequately.

To address this we propose a cross-layer optimization technique called recovery from Earlier Good State (REGS) that requires the protocol state achieved while the channel was in shadowed state to be discarded on channel recovery. That is, the operation of the protocols while the channel is good is not influenced by the decision made or state variables changed when the channel was temporarily shadowed. This achieved by check pointing the current protocol state on switching to a shadowed state and reverting to it on being informed of channel recovery. State boundaries are inferred by maintaining smoothed traces of signal strength and by using Hidden Markov Model training.

We applied REGS to TCP and the *SampleRate* algorithm and observed a significant performance improvement. The REGS technique was shown to be protocol independent and applicable at different layers of the protocol stack. The protocols that avoid or hide a bad state have been observed to have a complementary relationship with REGS in that while they minimize the effects of a bad state, REGS attempts to maximize the effects of a good state. We have learnt, through our performance studies that existing optimizations do not yield the same performance gains on the Environment Mobility model that have been shown with fast-fading or random error models. Also, some of these optimizations can be applied in conjunction with REGS to yield additional throughput improvements of about 50%.

A number of interesting questions on the impact of EM remain to be addressed. One interesting direction that we are currently exploring is the role of nodal mobility in relation with environmental mobility. Nodal mobility will distort the two-state model that we have presented, but to what extent and what will be the resulting impact on protocols remains to be seen. Furthermore, even though our diffraction models are generic, we have focused in our network study on the specific case of shadowing caused by human beings. We are also studying the impact of shadowing by objects with dimensions larger than humans - vehicles, for example. Finally, we had made the observation of the possibility of mutual benefit when REGS operates together with other optimization schemes. A thorough and holistic investigation can be conducted to identify the necessary conditions for this synergy of different optimization techniques.

2.6.3 GPU-Based Acceleration of Wireless Network Simulations

Network simulators have been widely used for performance evaluation of protocols and applications due to its scalability, flexibility and repeatability. At the same time, fidelity remains a top concern among network researchers. In recent years, there is clear consensus that detailed and accurate simulation models, especially for lower layers of the network protocol stack, are essential for high-fidelity performance evaluation of networks that rely on advanced antenna systems. On the other hand, with the integration of more detailed models, the computation cost of simulation based performance evaluation may grow prohibitively high. In the past, researchers have extensively studied parallel computing and grid computing to speed up simulation-based evaluations. Recently we observe that hardware acceleration has also been used in various application areas, partially due to the fact that the computation capability of specialized hardware, e.g. graphics processing units (GPU), DSP platform etc., has been advancing rapidly. In this project, we look at ways to reap the computational power of specialized hardware for acceleration of network simulation.

The graphics processing unit (GPU) is a dedicated graphics rendering device with substantial capability for processing graphics data sets. Consider two off-the-shelf graphics cards: GeForce 7900GTX processes up to 1.44 billion vertices per second and Radeon X1900 up to 1.3 billion vertices per second. Further, the advantage in computational power of GPUs against CPU has been widening. As of early 2006, nVidia GeForce 7800GTX had achieved 313 GFLOPS while high-end Pentium 4 can only deliver 25.6 GFLOPS. The GPU also has extremely fast access to texture memory, or its local onboard storage. The texture memory bandwidth in commercial cards is comparable to cache bandwidth in CPU. The nVidia GeForce 7900GTX supports memory bandwidth of 52.4 GB/sec with L2 cache bandwidth of about 100 GB/sec in Intel Pentium 4. The superior processing capability and fast on-board memory access are attributed to the stream processing model with spatial parallelism [41]. The rendering process, or the graphics hardware pipeline [42], includes three stages: application, geometry processing and rasterization. For modern GPUs, the last two stages are programmable, or can be customized with user-defined programs, known as vertex shader and fragment shader respectively. The vertex shader is executed on each point in the geometry processing stage while the fragment shader is used on each pixel in the rasterization stage. Substantial parallelism is built into modern GPUs. For example, in GeForce G70 series, there are 8 vertex processors and 24 fragment processors.

In recent years, GPUs have gained many followers for general-purpose computation, as surveyed by Owens et al. in [43], because of better price to performance ratio compared with CPU, faster evolution pace and improved flexibility and programmability. The community (see <http://gpgpu.org>) has collectively accumulated valuable experiences for GPU-based general-purpose computing.

Exploiting GPUs for network simulations has its own challenges. First, systematically identify the data parallelism inherent in network simulations. Fujimoto [44] suggests that in parallel discrete event simulation (PDES) the event-level causal constraints limit use of conventional parallel computing; in contrast, our study targets the data parallelism. Second, software abstraction is a necessity for using and developing GPU-accelerated simulation models; network researchers are not familiar with GPUs-based computing but demand short evaluation cycle. This dictates a programming framework for GPUs with well-defined APIs

that can be easily used by network modelers.

In this project [45], first, we propose a general simulation architecture using multiple CPUs, GPUs, and potentially extensible to other computing processors, to speed up execution of network simulations. Software abstractions are designed to transparently integrate GPU-based simulation modules with existing CPU-based ones and to facilitate use and development of GPU-based models. Second, we develop and implement two GPU-based simulation models to evaluate the benefits of using GPUs for protocol and system performance evaluation. The case study clearly demonstrates that GPU-implemented version can effectively speed up execution of simulation without observable degradation in accuracy of performance predictions. In some large scenarios, we achieve more than 10 times speedup. On the other hand, in network simulations there are also detailed models involving largely sequential operations or requiring extensive bit-wise operations, which are shown not suitable for GPUs-based acceleration. Consequently our study suggests that high fidelity network simulations can be accelerated by parallel use of CPU and GPU units available in off-the-shelf hardware. Guidelines proposed above must be followed to ensure best use of them in our high fidelity network evaluation platform.

As ongoing implementation effort, we are integrating GPU-implemented modules into existing simulation-based network evaluation platform using the architecture proposed above. Also, aggregation of events in PHY-layer simulation modules is specifically supported in order to exploit more data-parallelism. We are also investigating inclusion of FPGAs and cell processors for network simulations.

2.6.4 Modular, Transparent Device Driver

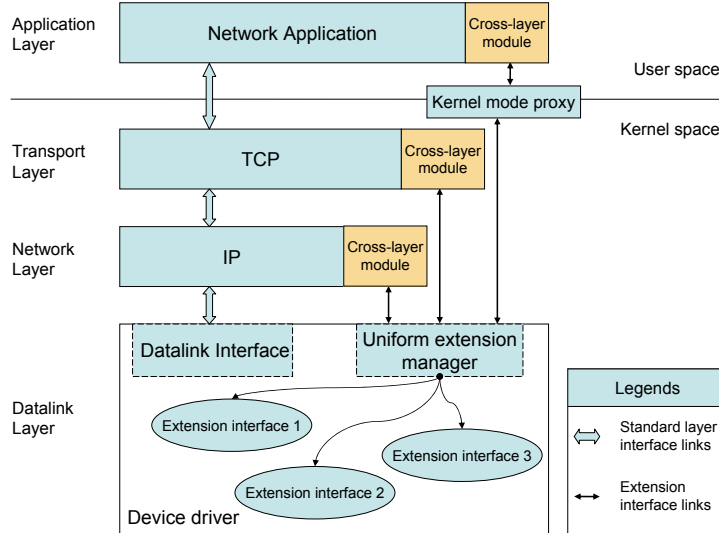


Figure 1: Architecture of the Uniform Extension Framework

As mentioned in prior sections, the traditional notion of a link is no longer well-defined in wireless environments, because characteristics of wireless links are now determined by several PHY/MAC control knobs and environmental factors. This implies that, in order to optimize network performance, PHY/MAC attributes should be exported to higher layer protocols in order to enable cross layer design and optimization, to promote spatial reuse through tuning of PHY/MAC parameters, and to allow implementation of new MAC functions other than those provided by IEEE 802.11. In particular, because new MAC functions may be in conflict with existing ones that have been implemented in the firmware of most IEEE 802.11 interface cards, there should be mechanisms for disabling selected MAC functionalities in the firmware and/or setting various parameters that are originally controlled by the firmware.

To deal with all the aforementioned issues, we have designed and implemented a *transparent device driver (TDD) layer* situated above the (proprietary) CUWin device firmware [102]. We leverage the Atheros chipset, and the open-source Madwifi driver in Linux and similar device drivers in NetBSD. Although commodity 802.11 interfaces typically partition the MAC functionalities between hardware/firmware on the card and the software driver running in the kernel, the Atheros chipset does not require the loading of firmware. The chipset instead relies on a *Hardware Access Layer (HAL)* module provided in the binary form only. The HAL module operates between the hardware and the device driver to manage many of the chip-specific operations and to enforce required FCC regulations. It is similar to firmware, in that it prevents users from setting invalid operating parameters, but implements fewer 802.11 functionalities than other firmware. More desirably, it provides an interface for changing various device parameters, including the minimum and maximum contention windows.

Architecture and Major Components: Figure 1 shows the architecture of the TDD. Different from the traditional layered approach, an extension-enabled device driver exports PHY/MAC parameters and events to higher-layer protocol modules. There are four major components in the TDD:

- **Extension-enabled device driver:** The device driver has been extended to export a set of PHY/MAC attributes and events in the form of *extension specification*. The specification serves as a service agreement between the device driver and a higher-layer protocol module that uses it. To implement an extension, a device driver implements the get/set handlers of the PHY/MAC parameter(s). It also defines events, provides the event information to the uniform extension manager, and notifies the manager upon occurrence of events.
- **Cross-layer control module:** A cross-layer control module implements a cross-layer design/optimization algorithm. As a client to the uniform extension manager, it registers itself with the uniform extension manager in order to use the facilities provided by the extension-enabled device driver. Through a generic interface, a control module can read and write PHY/MAC parameters exported by the driver. Also, it can subscribe to events of interest defined in an extension specification and provide the corresponding callback functions.

- **Uniform extension manager:** The uniform extension manager is the major component of the TDD. Conceptually, the uniform extension manager is responsible for (i) loading and unloading extensions, (ii) providing an API for cross-layer control modules to register events of interest and callback functions; (iii) allowing control modules to set/get PHY/MAC parameters via handlers registered by extensions; (iv) maintaining event definition and subscription, and (v) dispatching events to subscribing control modules.
- **Kernel mode proxy:** For user-space programs to gain access to the TDD in the kernel, we introduce a `jemlkernel mode proxy/eml` that serves as a “bridge” between the two entities. Each uniform extension function exported is assigned an unique system call number. The kernel mode proxy is responsible for translating a TDD-related system call and invoking the corresponding uniform extension function, and (ii) delivering events to the handler in the user space.

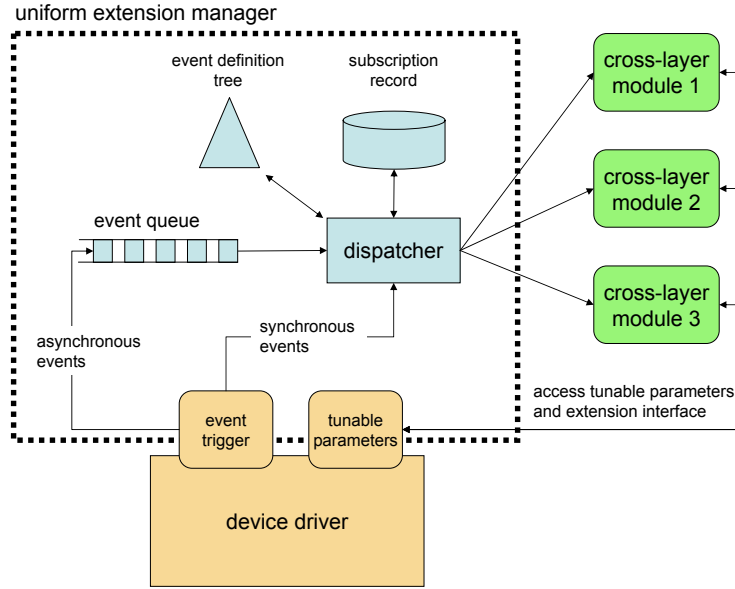


Figure 2: Uniform Extension Manager and Event Delivery

Internals of Uniform Extension Manager: Figure 2 shows the internals of the uniform extension manager and the data path in the event delivery mechanism.

The uniform extension manager maintains (i) the definition record of all the supported events in an event definition tree; and (ii) the list of subscribers of each event. An extension interface generates and delivers an event to the uniform extension manager (and subsequently cross-layer control modules that are interested in the event) by calling `TriggerEvent()`. A

cross-layer control module (un-)subscribes to an event with a callback function by calling `AddEventHandler()` (`RemoveEventHandler()`).

Depending on the type of events, there are two possible paths for delivering an event to the manager. A *synchronous event* is an event for which the device driver requires feedback from its subscribers. When a synchronous event is triggered, it is delivered by the dispatcher (in the uniform extension manager) immediately and the device driver that triggers the event waits until all the subscriber handlers are finished. An example of a synchronous event is a *transmit query*, in which prior to the transmission of a frame, the device driver may query the cross-layer control modules for recommendations on the transmit power, the channel on which the frame will be transmitted, or the data rate at which the frame will be transmitted. This facilitates realization of, for example, per-packet power control. Synchronous events make it possible for cross-layer control modules to make decisions upon occurrence of certain events. An *asynchronous event*, on the other hand, is a *notification* message sent by the device driver to the subscriber(s) of that event. Upon reception of an asynchronous event, the event trigger inserts the event into the event queue and wakes up the dispatcher. The dispatcher then delivers the event to the corresponding callback functions.

In principle, one can design any type of extension interfaces that export PHY/MAC attributes and events of interest in the TDD framework. The interested reader is referred to [103] for a detailed account. The TDD has the following salient features:

- **Controlled transparency:** The TDD provides a transparent and generic interface for higher-layer protocol modules to access, through well-defined APIs, a rich set of PHY/MAC attributes and functionalities in the device driver. Specifically, the following PHY/MAC attributes are available: (i) the transmit power level, (ii) the carrier sense threshold, (iii) the data rate, (iv) the receive signal strength index (RSSI), and (v) the channel used to transmit a frame/upon which a frame is received, and (v) the time instant at which a frame is scheduled for transmission/receive. Through an event subscription mechanism, higher-layer protocol modules can also receive timely update of channel status, without directly inserting callback functions in various places of the device driver.
- **Flexibility:** The design philosophy of the TDD (and at heart the uniform extension manager) is to provide minimum but crucial functionalities that enable implementation of complicated cross-layer design/control algorithms. The event subscription mechanism is simple, elegant, and allows *multiple* higher-layer protocol modules to subscribe, and be alerted of, PHY/MAC events of interest. They can also register with the event subscription mechanism their callback functions, allowing adequate actions to be taken upon event occurrence. Moreover, the TDD allows the time granularity at which PHY/MAC properties are controlled to be on a *per-packet* or *per-connection* basis, or *permanently* (i.e., until the property is reset).
- **Easy Integration and Portability:** Existing upper-layer protocol modules (e.g., routing daemons) can be extended to subscribe events of interest (e.g., frame reception status upon frame arrival), and figure in the information in their decision making. Through dynamic module loading and extension registration, an upper-layer protocol can realize cross-layer optimization if an extension has been implemented, and it falls back to the

normal operation if the required extension is not supported by the TDD. This ensures portability.

2.7 Task 6: Modeling and Control of Information Flow Patterns

In this task, we have studied several aspects of information flow patterns in networks. We applied game theory to the modeling of multipath routing, and developed new models for localization and sampling in sensor networks, wideband beamforming, and epidemic dissemination models for vehicular networks.

2.7.1 Game Theory Applied to Stochastic Multipath Routing

We introduced a novel game-theoretic stochastic multi-path routing framework as a proactive alternative to reactive route repair approaches [90]. The novelty of the proposed approach is that it formalizes the stochastic routing problem as an abstract game between two players: the designer of the routing algorithm, which is represented by *routers*, and an *attacker* that attempts to intercept packets. The goal is to minimize the impact of link and router failure by (1) computing multiple paths between source and destination and (2) selecting among these paths randomly to forward packets. Besides improving fault-tolerance, the fact that GTSR makes packets take random paths from source to destination also improves security. In particular, it makes connection eavesdropping attacks maximally difficult as the attacker would have to listen on all possible routes. We tested and validated GTSR through extensive simulations as well as experiments using PlanetLab. This work has been conducted as a collaboration with Professors Joao Hespanha, UCSB, and Stephen Bohacek, University of Delaware, both of which have been currently funded under ARO CTA projects.

2.7.2 Localization in Sensor Networks

We investigated empirically and analytically the impact of landmark placement on the accuracy of the coordinate system used for node localization in sensor networks [89]. We were the first to show analytically that placing landmarks on the periphery of the topology is optimal, i.e., yields the most accurate coordinate systems. Our empirical study is also the first one to consider not only uniform-, synthetic topologies, but also, non-uniform topologies resembling more concrete deployments. Our simulation results show that, in general, landmark placement strategies have significant performance impact only when the number of landmarks is low. In other words, if enough landmarks are used, random landmark placement yields comparative performance to placing landmarks on the boundary randomly or equally spaced. This is an important result since boundary placement, especially at equal distances, may turn out to be infeasible and/or too expensive in terms of communication and processing overhead.

2.7.3 Sampling in Sensor Networks

Much interest has been generated by proposals to reduce energy consumption in sensor networks with low bit (say 1-bit) A-D converters, but using an array of sensors with a much higher *spatial* density than required by the Nyquist rate. The reconstructed spatial signal suffers from (1) quantization error and (2) circuit error. Previous work focuses on reducing quantization error by spatial oversampling, with either PCM-style sampling or dither-based sampling. However, these proposals fail to decrease random errors associated with circuit noise, aperture uncertainty and comparator ambiguity.

We have proposed [127] an advanced dither-based sampling scheme with the goal of reducing both kinds of errors by increasing the density of the sensor nodes. The scheme distributes the task of improving the quantization error and random error among the nodes. The error of the scheme is shown to be $O(\frac{1}{r^{1/2}})$ for oversampling rate r . The maximum energy consumption per node is $O(\log(r))$. Finally, the bit rate of the scheme is $O(\frac{1}{r^{1/2} \log(r)})$ and it is robust against node failures in terms of a graceful degradation of reconstruction error.

2.7.4 Wideband Beamforming

Acoustic signals are wide band in the sense that the ratio of the bandwidth of an acoustic signal to the carrier frequency is very large; by comparison, normal communication channels are narrow band. The wide band of acoustic signals means that different frequencies in an acoustic signal are subject to different frequency and phase distortion in the acoustic ‘channel’. The problem considered in [129] is to adaptively process a speaker’s signal recorded by multiple receivers (microphones) in such a way as to reinforce the signal and reduce interference from other sources. The algorithm works by combining the signals from the different microphones after subjecting each signal to a digital filter whose weights are adaptively changed. The algorithm has been implemented in Matlab and tested in the laboratory.

The idea in [128] is extended to the situation in which the speaker is moving. This requires in addition to the beamforming scheme in [129], a procedure to locate, localize and track the speaker. The algorithm is modified to perform in a real environment by introducing two modes of adaptation that switch according to the speaker activity. The implementation of this modified system demonstrates SNR gain close to that of the original simulated system. It is robust to localization errors and non-ideal environmental effects.

We are currently investigating two problems. First, we wish to see the improvement that is possible by beamforming among a distributed system of several low power transmitters with omni-directional antennas. The idea is to introduce a phase shift in the carriers as a function of the feedback from the receiver. Theoretical and simulation results show that significant SNR gain is possible. The key obstacle in the implementation is to achieve synchronization among the distributed transmitters. The approach we are following is to combine the long-term accuracy of GPS with the short-term accuracy of inexpensive local oscillators.

Second, we are using actual RF measurements to characterize mobile channels for vehicular ad hoc networks (VANET). The FCC has allocated 75 MHz bandwidth (5.850 to

5.925 GHz) for applications in “Intelligent Transportation Systems) and IEEE 802.11p is an emerging standard. Our previous work has revealed the importance of accurate channel characterization [124]. We have taken extensive measurements and we are now formulating a mathematical model.

2.7.5 Epidemic Dissemination Models in Vehicle Networks

The recent advances in vehicular communications make possible the realization of vehicular sensor networks, i.e., collaborative environments where mobile vehicles equipped with sensors of different types (from toxic detectors to still/video cameras) inter-work to implement monitoring applications. We have recently designed and implemented MobEyes, a middleware solution that supports VSN-based proactive urban monitoring applications. MobEyes exploits wireless-enabled vehicles equipped with video cameras and a variety of sensors to perform event sensing, processing/classification of sensed data, and inter-vehicle ad hoc message routing. Since it is impossible to directly report the sheer amount of sensed data to the authority, MobEyes keeps the sensed data in the mobile node storage; on board processing capabilities are used to extract features of interest, e.g., license plates; mobile nodes periodically generate data summaries with extracted features and context information such as timestamps and positioning coordinates; mobile agents, e.g., police patrolling cars, move and opportunistically harvest summaries as needed from neighbor vehicles. Within the DAWN project, we have focused on several aspects related to epidemic dissemination and harvesting of the data, namely: (1) performance models that allow us to predict Mobeyes performance and can guide the planning of such systems; (2) bio inspired models that allow us to transfer to vehicular world a number of procedure successfully matures in nature; (3) mobility models that concisely capture the efficacy of given motion patterns for dissemination/harvesting, and; (4) wireless network security techniques that allow us to protect the “incentives” for dissemination in commercial environments.

Dissemination/Harvesting Analytic Model: We investigated the effectiveness of MobEyes in terms of complete index generation and of harvesting time [53]. In MobeEyes, regular nodes receive summaries from their neighbors (passive harvesting). The source periodically advertises its information to its neighbors. It can be extended up to k -hop relay scope for faster dissemination. These summaries will be harvested by the police agents (active harvesting). Obviously, the effectiveness of active harvesting depends also on passive harvesting. By modeling the progress of passive harvesting, we formulate the progress of active harvesting up to k -hop relay scope. Let N denote the number of nodes in the network and each node advertises its own summary. The speed of vehicles is v . The size of a network is $L \times Lm^2$. During the time slot Δt , a regular node travels a distance $r = v\Delta t$ and covers an area of $v\Delta t 2R$ where R is the radio range. The expected number of encountered nodes in this area is $\alpha = \rho v\Delta t 2R$. The distinct number of collected summaries by time step t is derived and simplified as

$$E_t = N - (N - k\alpha\eta) \left(1 - \frac{k\alpha\eta}{N}\right)^t$$

where η is a constant. This tells us that the distinct number of collected summaries is exponentially increasing and thus, as time tends to infinity, $E_t = N$. Let us define a random variable T to denote the time for a regular node to encounter any random node (i.e., thus receiving a summary from it). From the equation, we can derive the Probability Mass Function: $f_T(t) = \frac{k\alpha\eta}{N} \left(1 - \frac{k\alpha\eta}{N}\right)^t$, i.e., a modified geometric distribution with success probability $p = \frac{k\alpha\eta}{N}$. The average is given as $\mathbb{E}[T] = \mathbb{E}[T] = \frac{N}{k\alpha\eta} - 1 = \frac{L^2}{k\delta v^* \Delta t 2R\eta} - 1$. The equation shows that given a square area of L^2 , the average time for a regular node to collect a summary is independent of node density. In fact, it is a function of average relative speed and communication range. Intuitively, as node density increases (N increases), a node can collect more summaries during a given time slot, but this also means that it has to collect a higher number of summaries.

The expected number of distinct summaries harvested by time step t denoted as E_t^* is given as follows:

$$E_t^{k*} - E_{t-1}^{k*} = \gamma N \left(1 - \left(1 - \frac{E_{t-1}^k}{N}\right)^{k\alpha\eta}\right) \left(1 - \frac{E_{t-1}^{k*}}{N}\right)$$

where γ is a constant. We see that E_t^* grows much faster than E_t . During each time slot, the number of collected summaries by a regular node is constant (α), whereas it is a function of time and node density for an agent. As N (or node density) increases, we can see that the harvesting delay also decreases.

Bio-inspired Multi-agent Harvesting: We study how we can effectively coordinate the operations of multiple agents and guide them to seek most productive fields in a distributed manner using bio inspired concepts . Recall that due to high mobility and popularity of a certain number of roads, we have non-uniform stationary node distribution. In this work, we present a novel data harvesting algorithm in an urban sensing environment [54]. The proposed algorithm is designed based on biological inspirations such as (a) foraging behavior in *E. coli* bacteria, (b) stigmergy found in ants and other social insects, and (c) Levy flight found in foraging and general movement patterns. The proposed algorithm called datataxis enables the MobEyes agents to move to "information patches" where new information concentration is high. This algorithm is guided by a practical metric for information density estimate per road segment. In our data foraging strategy, an agent starts with a random walk until it encounters an information patch; then it performs a constrained walk to move toward a higher density region. When an agent encounters some other agents in the same region it moves to another regions using a conflict resolution algorithm that has been inspired by Levy jump, so that their work is not duplicated.

Mobility Models: The performance of data dissemination/harvesting depends on many different parameters including speed, motion pattern, node density, topology, data rate, and transmission range. This multitude makes it difficult to accurately evaluate and compare data gathering protocols implemented in different simulation or testbed scenarios. To assist in this performance prediction, we introduce Neighborhood Change Rate (NCR), a unifying measure that characterizes the "epidemic dissemination" efficiency of a specific traffic pattern and urban topology. NCR is independent of speed and density. We have analytically studied

the effective NCR for Markov type motion models, such as Real Track mobility model. A close-form expression has been derived. From this analytic solution, the NCR can be approximated from the initial scenario settings, such as velocity range, transmission range, and real map/street information. The close-form formula for NCR can be further employed to evaluate the ED process. The mathematical relationship between the dissemination index and the effective NCR is established and it allows predicting the performance of the ED process in realistic track motion scenarios. The experiment results showed that the analytic expressions for the NCR and for the evaluation of the ED process closely match the discrete-event simulations.

Secure Incentives for Data Dissemination: We proposed a secure incentive framework that can be used in epidemic-style data dissemination schemes. Most epidemic-style data dissemination schemes assume nodes' cooperativeness. However, due to non-cooperative behavior by selfish nodes or even malicious ones in the real-world scenario, such epidemic data dissemination may not be realized unless proper incentives and security mechanisms are taken into consideration. We proposed Signature-Seeking Drive (SSD), a secure incentive framework for epidemic data dissemination, and showed its usefulness in the commercial ad dissemination scenario in vehicular networks. Unlike currently proposed incentive systems, SSD does not rely on tamper-proof hardware or game theoretic approaches, yet leverages a PKI (Public Key Infrastructure) to provide secure incentives for cooperative nodes. In an advertisement dissemination scenario, we demonstrate that our SSD is robust in both incentive and security perspectives.

Future Work: There are several interesting avenues for future work on this subject. First, we will devise an effective data dissemination scheme in VANET. Data can be diffused in an area with high vehicle density in order to maximize the number of data holding nodes for a given period of time; and advance radio techniques, e.g., MIMO can be used for expedite the dissemination by exploiting multi-user diversity. Second, we will incorporate infrastructure (e.g., road-side infostations) to expedite data harvesting and investigate the optimal deployment strategy given mobility patterns. Basically we will work on how to deploy such infostations in the system so that we can maximize the harvesting rate. Third, we will study reactive query processing over vehicular sensor networks. We only considered the proactive meta-data harvesting [53]. We will consider the reactive data harvesting in the future. By reactive what we mean is that we send out a query and the query will be resolved on-the-fly by hopping a number of nodes. This procedure is quite similar to resolving SQL queries in a distributed way. Fourth, we will evaluate the performance given heterogeneous environments (i.e., mixture of different node types/radio techniques). For instance, in the warfare environment both vehicles and infantry (and possibly UAVs) may serve as mobile sensors. In urban warfare, the agents may actually be UAVs and thus, we will have heterogeneous sensors and agents. Fifth, we will continue studying NCR and Inter-contact time in order to investigate how mobility affects the routing protocol, such as its delivery ratio. We will develop its closed-form formula in the view of SINR of Physical Layer and compare its analytic results in Matlab with the simulation results in Qualnet. Finally, that security and privacy issues will be explored. We recently proposed a security/privacy

framework for vehicular sensor applications by proposing potential attack models, namely location tracking, denial of service, false data injection, and query confidentiality. Thus far, we only provide simple solutions for these attacks, but we will further generalize the security/privacy demands of vehicular sensor networks. In our current design, several central authorities such as certificate authority are involved. We plan to extend our framework and develop an incentive system that minimizes the need of central authorities.

3 Technology Transfer

One of the technology transfer avenues we have been pursuing is a collaboration with Wionics Research, part of the Realtek Group. We have ported an instantiation of DYNAMMA, our energy-efficient MAC framework, to a testbed consisting of UWB radios manufactured by Realtek.

Wionics Research, a subsidiary of Realtek Semiconductor Corporation, a public company based in Taiwan, develops wireless integrated circuit products for advanced wireless applications. Its products include wireless local-area network (WLAN) integrated circuits for personal computer (PC) and home multimedia systems, highly integrated tuner circuits for cable set-top box, liquid crystal display (LCD) televisions, and high-definition television (HDTV), and Ultra-Wideband (UWB) integrated circuits for home multimedia applications.

We have ported our scheduled-based medium access framework (DYNAMMA) to an FPGA-based testbed developed in collaboration with Wionics Research. In our setup, we used a Xilinx evaluation board with a Virtex-II pro FPGA and several customizable interfaces. The FPGA has a PowerPC hard macro that can be clocked up to 350MHz. The radio used for the testbed is based on RTU7010 chipset developed by Realtek. The radio implements the WiMedia physical layer standard and supports data rates from 53.3Mbps upto 480Mbps. The radio is controlled through the WiMedia MAC-PHY interface (MPI) standard.

In this architecture, MAC protocol functions are controlled using an embedded CPU and the low-level hardware MAC functions are implemented using a dedicated hardware (lower MAC). Typical functions provided by the lower MAC are: radio mode control, transmit/receive scheduling, transmitting a frame from memory through the MPI, and receiving a frame through MPI to the memory. The lower MAC IP is provided by the Wionics Research - Realtek Group.

We have been leveraging this technology transfer experience and our relationship with Realtek to expand the current MAC development testbed planned under our current DURIP award. The goal is to build a larger-scale, heterogeneous platform on which to test and evaluate MAC protocols. The resulting testbed will be made available to the other DAWN PIs as well as the research community at large. Currently we have a grad student working on the testbed as a summer interns at Wionics.

We have also contributed our energy models to the widely used GloMoSim and QualNet (by Scalable Network Technologies) network simulation platforms.

4 Publications by DAWN Investigators

4.1 Papers Published in Peer-Reviewed Journals and Books

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 - S. Rangarajan and J.J. Garcia-Luna-Aceves, ”Load-Balanced Routing in Ad Hoc Networks,” *Proc. 16th IEEE International Conference on Computer Communication Networks (ICCCN 2007)*, Honolulu, Hawaii, Aug. 13–16, 2007.
 - X. Wang, J.J. Garcia-Luna-Aceves, and H. Sadjadpour, ”Distributed Channel Access Scheduling for Ad Hoc Networks Using Virtual MIMO,” *Proc. 16th IEEE International Conference on Computer Communication Networks (ICCCN 2007)*, Honolulu, Hawaii, Aug. 13–16, 2007.
 - X. Wu, H. Sadjadpour and J.J. Garcia-Luna-Aceves, ”Analytical Modeling of Link and Path Dynamics and Their Implications on Packet Length in MANETs,” *Proc. SPECTS 2007: 2007 Int’l Symposium on Performance Evaluation of Computer and Telecommunication Systems*, San Diego, CA, July 16–18, 2007.
(**Best Paper Award**)
 - X. Wang, J.J. Garcia-Luna-Aceves, and H. Sadjadpour, ”Topology Aware Hybrid Channel Access Using Virtual MIMO,” *Proc. IEEE Symposium on Computers and Communication (ISCC ’07)*, Aveiro, Portugal, July 1–4, 2007.

- J. Boice, J.J. Garcia-Luna-Aceves, and K. Obraczka, “Disruption-Tolerant Routing with Scoped Propagation of Control,” *Proc. 2007 IEEE International Conference on Communications (ICC 2007)*, Glasgow, Scotland, June 24-28, 2007.
- R. Moraes, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, “CDMA Implementation for Many-to-Many Cooperation in Mobile Ad Hoc Networks,” *Proc. 25th Brazilian Symposium on Computer Networks and Distributed Systems*, Belem, Brazil, May 28–June 1, 2007.
- X. Wang and J.J. Garcia-Luna-Aceves, “Election based Hybrid Channel Access,” *Proc. IFIP Networking 2007*, Atlanta, GA, May 14–18, 2007.
- J. Boice, J.J. Garcia-Luna-Aceves, and K. Obraczka, “On-demand Routing in Disrupted Environments,” *Proc. IFIP Networking 2007*, Atlanta, GA, May 14–18, 2007. (**Best Paper Award**)
- R. Moraes, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, “Many-to-Many Communication: A New Approach for Collaboration in MANETs” *Proc. IEEE Infocom 2007*, Anchorage, Alaska, 6–12 May 2007.
- X. Wu, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, “Link Lifetime as a Function of Node Mobility in MANETs with Restricted Mobility: Modeling and Applications,” *Proc. WiOpt 2007: 5th Intl. Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks*, April 16-20, Limassol, Cyprus.

4.3 Non Peer-Reviewed Papers Published in Conference Proceedings

- I. Maric, A. Goldsmith, G. Kramer and S. Shamaï (Shitz), “On the Capacity of Interference Channels with a Cognitive Transmitter,” 2007 Workshop on Information Theory and Applications (ITA), UCSD, La Jolla, CA, Jan. 29 - Feb. 2, 2007. (Invited Paper)
- X. Wu, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, “An Analytical Framework for The Characterization of Link Dynamics in MANETs,” *Proc. IEEE MILCOM 2006*, Washington, D.C., October 23–25, 2006. (Invited Paper).
- R. Moraes, H. Sadjadpour, and J. J. Garcia-Luna-Aceves, “On The Link Ergodic Capacity of MIMO MANETs Using Cooperation,” *Proc. IEEE Asilomar Conference on Signals, Systems, and Computers*, Oct 29–Nov 1, 2006. (Invited Paper)

4.4 Manuscripts Submitted

- Xianren Wu, Hamid R. Sadjadpour and J.J. Garcia-Luna-Aceves, “Link Dynamics in MANETs with Restricted Node Mobility: Modeling and Applications,” Submitted to IEEE Transaction on Wireless Communications.

- C. T. K. Ng, D. Gunduz, A. J. Goldsmith and E. Erkip, Optimal Power Distribution and Minimum Expected Distortion in Gaussian Layered Broadcast Coding with Successive Refinement, submitted to IEEE Transactions on Information Theory, 2007.
- C. T. K. Ng and A. J. Goldsmith, The Impact of CSI and Power Allocation on Relay Channel Capacity and Cooperation Strategies, submitted to IEEE Transactions on Wireless Communications, 2007.
- Simone Merlin, Nitin H. Vaidya, and Michele Zorzi, "Resource Allocation in Multi-Radio Multi-Channel Multi-Hop Wireless Networks," Technical Report, UIUC, July 2007.
- Lu-Chuan Kung, Jihyuk Choi, Jennifer C. Hou, Yan Cao, I-Hong Hou, Ray Lam, Yong Yang, "CUWiN: Towards building a open wireless mesh network for cross layer design and optimization", submitted to IEEE Network Magazine, August 2007.
- Kyung-Joon Park, LaeYoung Kim, Jennifer C. Hou, T. Baser, submitted to IEEE Journal of Selected Areas in Communications, Special Issues on Game Theory in Communications Systems, August 2007.
- Kyung-Joon Park, LaeYoung Kim, and Jennifer C. Hou, "Coordinating the interplay between physical carrier sense and power control in CSMA/CA wireless networks," submitted to IEEE INFOCOM 2008, July 2007.
- Tae-Seok Kim, Yong Yang, and Jennifer C. Hou, "Modeling of CSMA-based multi-rate wireless networks and its application towards improving network throughput," submitted to IEEE INFOCOM 2008, July 2007.
- Zheng Zeng, Yong Yang, and Jennifer C. Hou, "How physical carrier sense affect protocol capacity: modeling and analysis," submitted to IEEE INFOCOM 2008, July 2007.
- Yan Gao, Jennifer C. Hou, and Hoang Nguyen, "Topology control for maintaining network connectivity and maximizing network capacity under the physical model," submitted to IEEE INFOCOM 2008, July 2007.
- F. Benbadis, K. Obraczka and J. Cortes, "Exploring Landmark Placement Strategies for Self-Localization in Wireless Sensor Networks", submitted to the EURASIP Journal of Applied Signal Processing Special Issue on Signal Processing for Location Estimation and Tracking in Wireless Environments.
- T. Spyropoulos, T. Turletti and K. Obraczka, "Routing in Delay-Tolerant Networks Comprising Heterogeneous Node Populations", submitted to the IEEE Transactions on Mobile Computing.
- Luiz Filipe M. Vieira, Archan Misra, Mario Gerla. Performance of Network-Coding for Multicast Applications in Rate-Diverse Wireless Environments Submitted to MILCOM 2007

- Biao Zhou, Mario Gerla, and Jerome Haerri. NCR: A Unifying Parameter to Characterize and Evaluate Data Dissemination Scenarios, and Its Analytic Study. Submitted to MILCOM 2007.
- Soon Y. Oh, Mario Gerla, Pengkai Zhao, Babak Daneshrad, Guangyu Pei, Jae H. Kim. MIMO-CAST: A Cross-Layer Ad Hoc Multicast Protocol Using MIMO Radio. Submitted to MILCOM 2007
- Uichin Lee, Eugenio Magistretti, Mario Gerla, Paolo Bellavista, Antonio Corradi. Opportunistic Dissemination and Harvesting of Urban Monitoring Information in Vehicular Sensor Networks. Submitted to IEEE Trans. Vehicular Technology.
- Uichin Lee, Eugenio Magistretti, Mario Gerla, Paolo Bellavista, Pietro Lio, Kang-Won Lee, Bio-inspired Multi-Agent Data Harvesting in a Proactive Urban Monitoring Environment. Submitted to Ad Hoc Networks journal.
- S. Timofeev, A. Bahai, and P. Varaiya, "Adaptive acoustic beamformer with source tracking capabilities," *IEEE Transactions on Signal Processing*, 2007. Submitted.

4.5 Ph.D. and M.S. Theses Completed

The following 10 theses were completed during the past year:

- C. T. K. Ng, Cooperation and Optimal Cross-Layer Resource Allocation in Wireless Networks, Stanford University, Stanford, CA, 2007.
- Yalin Sagduyu, "Medium Access Control and Network Coding for Wireless Information Flows," Ph.D. Thesis, University of Maryland, July 2007.
- Tolga Girici, "Resource Allocation Schemes for OFDMA-based Wireless Systems with Quality of Service Constraints," Ph.D. Thesis, University of Maryland, September 2007.
- Azadeh Faridi, "Cross-Layer Distortion Control for Delay-Sensitive Sources," Ph.D. Thesis, University of Maryland, August 2007.
- Song Li, "Hiding Traffic Flows in Wireless Communication Networks," Ph.D. Thesis, University of Maryland, August 2007.
- Chunyu Hu, MAC-centric resource management in wireless networks, Ph.D. Thesis, UIUC, October 2006.
- Z. Chen, "Dynamic Spatial Backoff in Fading Environment," M.S. Thesis, ECE Department, UIUC, 2007.
- Rahul Ravindran, "Bidding based Scheduling for Channel Access in Mobile Ad Hoc Networks" M.S. Thesis, Computer Engineering, UCSC, June 2006..

- Sudharsan Rangarajan, "On demand Loop Free Multipath Routing in Ad hoc Networks using Source Sequence Numbers," M.S. Thesis, Computer Engineering, March 2007.
- Jay Boyce, "Routing in Disruptive Environments," M.S. Thesis, Computer Engineering, March 2007.

5 Honors and Awards

The faculty participating in DAWN received the following honors and awards. The list is provided in alphabetical order according to the last names of principal investigators.

5.1 Tony Ephremides

- Distinguished Lecturer of the IEEE Communication Society
- Co-Chair of NSF sponsored workshop on Cross-Layering in Networks, Washington, DC August 2007
- Invited Plenary Speaker at the IEEE Communicatin Theory Workshop, May, 2007, Sedona, Arizona
- Invited Plenary Speaker at the MEDHOCNET Conference, Corfu, Greece
- Invited Plenary Speaker at the IEEE section meeting , Reston, Virginia
- Panelist for European Union Research Program Review , Brussels, Belgium
- External Examiner for PhD Dissertations at EPFL, Lausanne, Switzerland, KTH, Stockholm, Sweden, and University of Paris 6
- Elector for Faculty selection at the University of Cyprus
- Editor-in-Chief foe Foundations and Trends in Networking, NOW Publishers, U.K.

5.2 J.J. Garcia-Luna-Aceves

- Best Paper Award:
J. Boice, J.J. Garcia-Luna-Aceves, and K. Obraczka, “On-demand Routing in Disrupted Environments,” *Proc. IFIP Networking 2007*, Atlanta, GA, May 14–18, 2007.
- Best Paper Award:
X. Wu, H. Sadjadpour and J.J. Garcia-Luna-Aceves, “Analytical Modeling of Link and Path Dynamics and Their Implications on Packet Length in MANETs,” *Proc. SPECTS 2007: 2007 Int’l Symposium on Performance Evaluation of Computer and Telecommunication Systems*, San Diego, CA, July 16–18, 2007.
- Best Paper Award:
V. Rajendran, K. Obraczka, and J.J. Garcia-Luna-Aceves, “A DYNAmic Multi-channel Medium Access Framework for Wireless Ad Hoc Networks,” *Proc. IEEE MASS 2007*, Pisa, Italy, Oct. 9–11, 2007.
- Who’s Who in America, 2006–
- Who’s Who in The World, 2008–

- Keynote Speaker, *IEEE LOCAN 2006: 2nd International Workshop on Localized Communication and Topology Protocols for Ad hoc Networks*, Vancouver, Canada, October 9, 2006.
- Member of the Technical Program Committee of several conferences, including ACM Mobicom 2007, IEEE Infocom 2007, and IEEE MASS 2006.

5.3 Mario Gerla

- Best Paper Award:
Sewook Jung, Uichin Lee, Alexander Chang, Daeki Cho, and Mario Gerla "BlueTorrent: Cooperative Content Sharing for Bluetooth Users," *Proc. IEEE PerCom 2007*, White Plains, NY, March 19–23, 2007.
- General Chair, Twelfth Annual International Conference on Mobile Computing and Networking (MobiCom 2006)

5.4 Andrea Goldsmith

- Best Student Paper Award:
Chris T.K. Ng, Deniz Gunduz, Andrea Goldsmith, and Elza Erkip, "Minimum Expected Distortion in Gaussian Layered Broadcast Coding with Successive Refinement," *IEEE International Symposium on Information Theory (ISIT)*, Nice, France, June 2007.
- Technical Program Co-Chair of the 2007 IEEE International Symposium on Information Theory.
- Serving as 2nd Vice President of the IEEE Information Theory Society.
- Distinguished Lecturer of the IEEE Communications Society
- Member of the IEEE Communications Society Board of Governors and the IEEE Information Theory Society Board of Governors.
- Plenary speaker at the Wireless World Conference in Palo Alto, May 2007
- Plenary speaker at the American Control Conference in New York City, July 2007.

5.5 Jennifer Hou

- Technical Program Co-chair of ACM Mobicom 2007
- Technical Program Co-Chair of IEEE INFOCOM 2008.

- Editorial board member of IEEE Trans. on Computers, IEEE Trans. on Parallel and Distributed Systems, IEEE Trans. on Wireless Communications, IEEE Trans. on Mobile Computing, IEEE Wireless Communications Magazine, and ACM Trans. on Sensor Networks.
- Invited speaker at Womens Institute in Summer Enrichment (WISE 2007), University of California, Berkeley, June 2007.
- Ray Lam (Professor Hou's student) has been awarded a prestigious R C Lee Centenary Scholarship from the Hong Kong Government.
- Yong Yang (Professor Hou's student) has been awarded the Vodafone Graduate Fellowship.

5.6 Katia Obraczka

- Best Paper Award:
J. Boice, J.J. Garcia-Luna-Aceves, and K. Obraczka, "On-demand Routing in Disrupted Environments," *Proc. IFIP Networking 2007*, Atlanta, GA, May 14–18, 2007.
- Best Paper Award:
V. Rajendran, K. Obraczka, and J.J. Garcia-Luna-Aceves, "A DYNAMIC Multi-channel Medium Access Framework for Wireless Ad Hoc Networks," *Proc. IEEE MASS 2007*, Pisa, Italy, Oct. 9–11, 2007.

5.7 Hamid Sadjadpour

- Best Paper Award:
X. Wu, H. Sadjadpour and J.J. Garcia-Luna-Aceves, "Analytical Modeling of Link and Path Dynamics and Their Implications on Packet Length in MANETs," *Proc. SPECTS 2007: 2007 Int'l Symposium on Performance Evaluation of Computer and Telecommunication Systems*, San Diego, CA, July 16–18, 2007.
- Co-Chair of International Wireless Communications and Mobile Computing (IWCMC) 2007 conference.
- Technical program committee member for SPAWC2007, Globecom 2007, and INFOCOM 2008.

5.8 Pravin Varaiya

- Docteur Honoris Causa, L'Institut National Polytechnique de Grenoble, 2006
- Fellow, American Academy of Arts and Sciences, 2006
- Distinguished Visiting Professor, University of Hong Kong, December 2006–February 2007

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