Annual Report for 2002-2003:

Report on Efficient Provisioning for Services in Large-Scale Ad Hoc Wireless-Wired Networks

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1. Introduction

The ubiquity of small mobile devices is enabling new models of computation and communication for the next generation networks. One very promising next generation technology includes ad hoc networks in general. The field of ad hoc networks has attracted a lot of research attention recently and many ad hoc networking protocols have been proposed. Unfortunately, there has been little work on service provisioning and evaluation for ad hoc networks, especially for large-scale ad hoc networks. In this work the issue of service provisioning and evaluation in large-scale mobile ad hoc networks is addressed.

Previously, three main components have been identified in our framework for service provisioning: (a) Resource discovery, (b) Rendezvous mechanisms, and (c) Multicast-based micro mobility (M&M).
In addition, in our on-going work we have explicitly identified and studied two more architectural components: (i) Heterogeneous wired-wireless networks, and (ii) Mobility modeling and analysis.
During the last year, significant progress has been made on research for these individual components. The progress report and lessons learned is presented in sections 2 and 3. Furthermore, several future directions have been identified to continue the research, mainly concentrating on the 'integration' of the above components and illustration of the utility, performance gain and robustness of our architectures. Future directions are addressed in more detail in section 4.

2. Progress Report

Progress has been made on the following five fronts: (1) Scalable resource discovery and contact-based architectures, (2) Geographic routing and rendezvous mechanisms, (3) Multicast-based micro mobility, (4) Heterogeneous wired-wireless networks, and (5) Mobility modeling and analysis. Progress in each area is detailed in this section along with a publication list for each area. (The publication lists include papers accepted and/or published within the last year that had direct relation to this project. Previous publications, non-refereed technical reports or publications under submission/preparation are not included in this section).

2.1 Resource Discovery and Contact-based Architectures

Four different architectures; called *CARD*, *MARQ*, *TRANSFER* and *ACQUIRE*, respectively, were designed, simulated and evaluated based on the contact-based approach. These architectures have been shown to perform very well for short transfers and query-like traffic in large-scale wireless networks. The first two architectures, *CARD* and *MARQ*, use a pro-active approach that selects ***and*** maintains contacts. *CARD* uses zone-edge information to select useful contacts, while *MARQ* exploits mobility by choosing contacts moving away from the zone. The third architecture, *TRANSFER*, on the other hand, uses a re-active approach, by choosing contacts on-the-fly when the query is issued. The reactive nature of this protocol reduces the maintenance overhead and is more resilient to network dynamics. The fourth architecture, *ACQUIRE*, is geared towards multi-variable query resolution, where the queries have more complex semantics.

All the above architectures were evaluated through extensive simulations and compared to existing state-of-the-art wireless routing protocols. Our contact-based architectures showed significant reduction in communication overhead and power savings over existing protocols (including ad hoc routing, zone routing, minimum dominating sets and clusters, and geographic-based smart flooding).

- **Publications** relating to resource discovery and contact-based architecture:

  - A. Helmy, "*TRANSFER*: Transactions Routing for Ad-hoc Networks with eFficient EneRgy", *IEEE GLOBECOM*, San Francisco, CA, December 2003.

  - A. Helmy, S. Garg, P. Pamu, N. Nahata, "Contact Based Architecture for Resource Discovery (*CARD*) in Large Scale MANets", *Third IEEE/ACM International Workshop on Wireless, Mobile and Ad Hoc Networks (WMAN), part of IEEE/ACM IPDPS*, Nice, France, April 2003.

  - A. Helmy, "Mobility-Assisted Resolution of Queries in Large-Scale Mobile Sensor Networks (*MARQ*)", *Computer Networks Journal - Elsevier Science, Special issue on Wireless Sensor Networks*. Accepted, to appear August 2003 (In Press).

  - N. Sadagopan, B. Krishnamachari, A. Helmy, "Active Query Forwarding in Sensor Networks (*ACQUIRE*)", *AdHoc Networks Journal - Elsevier Science*. Accepted, to appear Fall 2003.

  - N. Sadagopan, B. Krishnamachari, A. Helmy, "The *ACQUIRE* Mechanism for Efficient Querying in Sensor Networks", *First IEEE International Workshop on Sensor Network Protocols and Applications (SNPA), in conjunction with IEEE ICC*, Anchorage, May 2003.

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- A. Helmy, "Contact-extended Zone-based Routing for Transactions in Ad Hoc Networks", May 2003. (Accepted with revision to the *IEEE Transactions on Vehicular Technology*).

- Shao-Cheng Wang, Ahmed Helmy, "Effects of Small Transfers and Traffic Patterns on Performance and Cache Efficacy of Ad Hoc Routing", *The ACM MOBICOM Conference*, San Diego, CA, Sept 2003. (Refereed Poster and Extended Abstract)

2.2 Rendezvous Mechanisms and Geographic Routing

For storage/retrieval types of services, we propose a rendezvous architecture based on consistent distributed hashing and geographic routing techniques. Instead of hashing to a specific *location*, however, we introduce the rendezvous '*regions*' (*RR*) architecture. The mechanistic and algorithmic details were specified, simulated and evaluated. The *RR* architecture was shown to be scalable, robust to node failures and resilient to network dynamics and mobility (since mobility effects are dampened by the use of regions). A detailed comparison with the geographic hash table (*GHT*) approach was conducted and produced results clearly favoring the *RR* approach under diverse operating conditions.
In addition to the *RR* approach, this direction of research investigated the effect of location errors on geographic routing; a subject that has not been studied before. Location errors may be due to (a) localization-system errors (e.g., GPS), (b) location discovery protocol errors or inconsistency, and (c) mobility induced inaccuracy. Three different studies were conducted on the effects of errors on geographic routing, all of which have clearly shown the drastic effects that (even small) errors can have on geographic routing.
Previously, geographic routing (e.g., *GPSR*) using a combination of greedy routing and face-routing, was shown to be correct and efficient in the absence of location errors. However, we have shown for the first time that under cases of location errors geographic routing protocols violate the correctness conditions, and their performance drops drastically. We have proposed fixes and mobility prediction techniques to alleviate the effects of location errors on geographic routing. We have also shown that the *RR* architecture is much more robust in the face of location errors than *GHT*.
These studies have led us to believe that there is a strong reason to re-visit geographic routing architectures, and to attempt to design architectures to relax the assumption of 'exact' location information for their correctness. Currently, we are integrating the notion of contact-based routing and the *RR* architecture to achieve this goal.

- **Publications** relating to geographic routing and rendezvous regions:

  - K. Seada, A. Helmy, "Rendezvous Regions: A Scalable Architecture for Service Provisioning in Large-Scale Mobile Ad Hoc Networks", *ACM SIGCOMM Conference*, Karlsruhe, Germany, August 2003. (Refereed Poster). [Extended abstract to appear in *ACM SIGCOMM Computer Communications Review*].

  - Karim Seada, Ahmed Helmy, Ramesh Govindan, "On the Effect of Localization Errors on Geographic Face Routing in Sensor Networks", *The First ACM Conference on Embedded Networked Sensor Systems (SenSys)*, Los Angeles, CA, November

2003. (Refereed Poster) [Extended 2-page abstract to appear in the conference proceedings]

- Y. Kim, J. Lee, A. Helmy, "Impact of Location Inconsistencies on Geographic Routing in Wireless Networks", Sixth ACM International Workshop on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWIM), in conjunction with ACM MOBICOM, San Diego, CA, September 2003. (Short paper) [Acceptance rate: 14.5%. Ranked 16^{th} of 103 submissions]

- K. Seada, A. Helmy, "Rendezvous Regions: A Scalable Architecture for Service Location and Data-Centric Storage in Large-Scale Wireless Networks", ACM MOBICOM Conference, San Diego, CA, Sept 2003. (Refereed Poster and Extended abstract)

- Karim Seada, Ahmed Helmy, Ramesh Govindan, " On the Effect of Location Inaccuracy on Geographic Face Routing in Wireless Networks", *The ACM MOBICOM Conference*, San Diego, CA, Sept 2003. (Refereed Poster and Extended abstract)

- D. Son, J. Park, A. Helmy, "Mobility-Induced Location Errors and its Effect on Geographic Routing in Ad Hoc Networks: Analysis and Improvement using Mobility Prediction", *The ACM MOBICOM Conference*, San Diego, CA, Sept 2003. (Refereed Poster and Extended Abstract)

2.3 Multicast-based Mobility (M&M)

Continued research on the M&M architecture established a framework for micro-mobility protocols, in which buffering and routing prediction mechanisms are parametrized and set to improve performance of given scenarios and technologies. Our work studied proactive and reactive handoff scenarios and coverage gap scenarios over a rich set of network topologies. The results show that proper setting of the M&M parameters achieves significant performance improvement over state-of-the-art micro-mobility protocols such as Hawaii and Cellular-IP.

- **Publications** relating to multicast-based mobility:

- A. Helmy, M. Jaseemuddin, Ganesha Bhaskara, "Multicast-based Mobility: A Novel Architecture for Efficient Micro-Mobility", *IEEE Journal on Selected Areas in Communications (JSAC), Special Issue on All-IP Wireless Networks*. Accepted, to Appear Spring 2004.

- A. Helmy, M. Jaseemuddin, G. Bhaskara, "Efficient Micro-Mobility using Intra-domain Multicast-based Mechanisms (M&M)", *ACM SIGCOMM Computer Communications Review (CCR),* Volume 32, Number 5, pages 61-72, November 2002.

- G. Bhaskara, A. Helmy, S. Gupta, "Micro Mobility Protocol Design and Evaluation: A Parameterized Building Block Approach", *IEEE Vehicular Technology Conference (VTC), Symposium on IP Mobility,* October 2003.

2.4. Hetergeneous wired-wireless networks

Wireless access points (e.g., 802.11 base stations) are becoming quite ubiquitous and their capacity/data rates are increasing rapidly. However, their coverage is quite limited. Hence, to achieve reasonable wireless network coverage we believe it is imperative to extend such base station-based networks using ad hoc networks in an integrated heterogeneous architecture. Two approaches are investigated for integrating the wired/infrastructure-based networks with ad hoc networks. The first extends the micro-mobility approach to integrate multi-hop wireless networks at the leaves (as opposed to the current last-hop-wireless networks). For this we are investigating and defining the problem in the context of (extensions and variants of) the micro-mobility protocols. The second approach extends the ad hoc network by adding infrastructure in the form of a small number of base stations or wires (shot cuts) between static nodes.

A small world analysis was adopted for this study that shows the efficacy of adding only a few number of short cuts (links or base stations) to achieve drastic reduction in the average path length in the ad hoc network. These short cuts need not be random but may extend only a small fraction of the network diameter.

These two wired-wireless integration approaches are still under active research. Similar ideas of small world are also investigated to establish security associations between users in ad hoc and heterogeneous networks. Related work on security in ad hoc networks includes work on 'trust routing' which is part of on-going and future work.

- **Publications** relating to wired-wireless networks, small worlds:

  - A. Helmy, "Small Worlds in Wireless Networks", *IEEE Communications Letters*. Accepted, to appear August 2003 (In Press).

  - S. Tanachaiwiwat, P. Dave, R. Bhindwale, A. Helmy, "Secure Locations: Routing on Trust and Isolating Compromised Sensors in Location-aware Sensor Networks", *The First ACM Conference on Embedded Networked Sensor Systems (SenSys)*, Los Angeles, CA, November 2003. (Refereed Poster) [Extended abstract to appear in the conference proceedings]

2.5. Mobility modeling and analysis

Most studies on ad hoc networks model mobility using random-based techniques; mostly using the random waypoint model. Our studies using highway, manhattan, group, expansion and contraction mobility models, among others, have shown that the random waypoint model does not capture main characteristics of some realistic mobility models (such as vehicular networks). In fact, we have shown that ad hoc routing protocols are sensitive to the mobility models, and exhibit widely varying performance under different models. Specifically, movement correlation among nodes greatly affects network connectivity and hence has a great impact on the performance of ad hoc protocols.

We also conducted a related study on the statistics of link and path duration, refuting a commonly used assumption that link duration distribution is exponential, and establishing the conditions under which the ‘path’ duration distribution may be approximated as exponential distribution.

- **Publications** relating to mobility modeling:

  - F. Bai, N. Sadagopan, A. Helmy, "The IMPORTANT Framework for Analyzing the Impact of Mobility on Performance of Routing for Ad Hoc Networks", *AdHoc Networks Journal - Elsevier Science*. Accepted, to appear Fall 2003 (In Press).

  - F. Bai, N. Sadagopan, A. Helmy, "IMPORTANT: A framework to systematically analyze the Impact of Mobility on Performance of RouTing protocols for Adhoc NeTworks", *IEEE INFOCOM (The 22nd Annual Joint Conference of the IEEE Computer and Communications Societies)*, San Francisco, CA, April 2003. (Acceptance rate: 20% of 1078 submissions)

  - N. Sadagopan, F. Bai, B. Krishnamachari, A. Helmy, "PATHS: analysis of PATH duration Statistics and their impact on reactive MANET routing protocols", *ACM MobiHoc (The Fourth ACM International Symposium on Mobile Ad Hoc Networking and Computing)*, Annapolis, MD, June 2003. (Acceptance rate: 15% of 189 submissions)

3. Lessons Learned on This Project

(1) Resource Discovery and Contact-based Approaches

- Small transfers/transactions and resource discovery in large-scale wireless networks exhibits drastically different performance than long-lived connections traditionally studied in ad hoc networks.
- The contact-based approach gives a great performance advantage for small transfers and resource discovery, especially when the query to dynamics ratio is moderate to high (i.e., when the nodes are not idle)
- Compared the contact based approach to flooding, on-demand routing with cache (e.g., DSR, AODV), expanding ring search, smart-flooding (geographic based or counter-based), minimum dominating sets and cluster-based approaches, zone based routing (using bordercast). The contact-based approach has a clear advantage in overhead savings for small transfers in large-scale networks.

(2) Geographic Routing and Rendezvous

- Location errors (even small errors) due to noisy localization, inconsistency (in location discovery protocols), or mobility, affect the performance of geographic routing drastically.

- Investigated and suggested ways to improve performance of geographic routing (e.g., *GPSR* and *GHT*) using enhanced planarization algorithms, and mobility prediction schemes
- Use of 'rendezvous regions' instead of points (as in *GHT*) increases the stability of the protocol in terms of dampening mobility effects, and decreasing sensitivity to location errors.
- Performance of the rendezvous regions (*RR*) storage/retrieval systems benefit most with the lookup-to-insertion ratio is higher
- Conducted detailed comparison with *GHT* and its variants (enhancements) and illustrated the performance and stability gain of our rendezvous regions approach

(3) Micro-Mobility and Efficient Hand-off

- Buffering and routing are among the main factors affecting the hand-off performance of micro-mobility protocols. Buffering (as in Hawaii) leads to reduced packet loss, but increases delays, jitter, re-ordering depth and storage requirements. Efficient routing (as in Cellular-IP) decreases delays and storage requirements, but leads to increased packet loss.
- For re-active handoff (as in 802.11) where the mobile can only talk to one base station at a time, or where coverage includes gaps (due to deployment or obstacles), prediction schemes (sending packets to expected base stations ahead of time) improve performance notably.
- The multicast-based mobility (M&M) framework provides mechanisms for pro-active and re-active handoff, via a novel architecture (the CAR-Set) for choosing the number of base stations participating in the prediction. It also provides a wide range of buffering and routing parameters, the tuning of which gives excellent performance for the various operating points.
- M&M was compared through extensive simulations to cellular-IP and Hawaii and the significant performance gain was clearly shown.

(4) Heterogeneous Wired-wireless Network Design

- For heterogeneous wired-wireless networks the introduction of short cuts (via wires or base stations) can be shown to improve performance drastically by creating "a small world" in the network.
- In large-scale wireless networks, adding only a few wired nodes (e.g., base stations) improves performance drastically by cutting down the average (wireless) path length. Preliminary results show that 15 base stations (in 1000 node topology) reduce average path length by half. Further study is on-going.

(5) Mobility Modeling, Analysis and Effects

- Mobility affects performance of ad hoc routing drastically. Random way point models are not able to capture core characteristics of realistic mobility.

- Investigated manhattan, freeway and group mobility models and developed metrics to capture the correlation inherent therein.
- Illustrated that these models exhibit different performance for ad hoc routing
- Showed that average *link* duration is *not* exponential. Rather, average *path* duration may be approximated by exponential distribution for moderate to high mobility (>10m/s), and moderate/high hop count (>2 hops)
- On-going research on enriching the mobility models using contraction, expansion, and hybrid models indicates the need for further research in this area.

General Summary

- There is a need to re-visit geographic-based architectures for ad hoc networks and to introduce architectures that work robustly and efficiently with approximate and noisy location information.

- Special care should be given to traffic patterns when designing services and routing protocols for wireless and ad hoc networks. Networking protocols may exhibit widely varying performance for small transfers vs. long-lived connections.

- Micro-mobility protocols exhibit drastically different performance depending on the hand-off scenario which is in turn a function of the underlying access and radio technology, e.g., 802.11 with reactive-handoff can be handled efficiently using prediction schemes.

- To understand and improve the performance of ad hoc protocols it is imperative to understand a rich set of mobility models and use a mobility-rich framework for the evaluation and comparison.

4. Future Plans

Our proposed plans for future research continue the previous directions, and go beyond them to explore several architectures for integrating contact-based and *RR* architectures, integrating wired and wireless ad hoc networks, using small world analysis for heterogeneous networks and for building security associations, further studies on practical multicast-based micro mobility and mobility modeling, integration of radio resource measurements into our algorithms and protoocls in addition to plans for implementations and demonstration of these technologies.

Integration of contact-based and rendezvous region architectures for approximate location routing:

Motivated by our illustrated need to re-visit geographic routing architectures and to relax the ‘exact’ location requirement, we propose to investigate architectures for service and routing using approximate location information. More specifically, we propose the integration of the rendezvous regions (*RR*) approach and the contact-based approach for better robustness to location errors. The promise of this direction stems from several observations. We have illustrated that the *RR* architecture is more robust to location errors and mobility effects than *GHT*. Routing to regions is inherently less error-prone than routing to a point. In addition, using contact locations for routing (instead of neighbor node location) is tolerant to a larger margin of error (e.g., 6 hops vs. 1 hop for conventional geographic routing). In this integrated architecture routing through contacts will be used to perform look-up and insertion operations in a specific geographic region. Furthermore, this architecture does not require all nodes to be location-aware, but only a small fraction of the nodes may have location-awareness (e.g., GPS capability). Also, possible extensions of the contact-based mechanisms in this context include a geographic-assisted contact selection protocol to take advantage of approximate geographic information to select useful contacts.

Integration of wired/infrastructure-based and wireless ad hoc networks:

We believe that future networks will be an integration of various kinds of networks, mainly wired networks, infrastructure-based (base station) networks, and mobile ad hoc wireless networks. Such integration, however challenging, provides added capacity, flexibility and coverage to existing networks. We propose to investigate two main approaches to integrate wired and wireless networks.

The first approach extends micro-mobility approaches to encompass multi-hop wireless networks, as opposed to the current last-hop-wireless networks. This approach may be promising when the communication between wired and wireless nodes is significant. Since mirco-mobility protocols have been designed for efficient handoff, this may help achieve reasonable handoff in the integrated wired-wireless networks. However, the definition of 'handoff' (as being between base stations) needs to be re-visited and refined. This approach is also fit for extending 802.11 coverage using ad hoc networks

The second approach extends the ad hoc network with infrastructure (or short cuts). This may be useful in situations where most users are mobile (as in rapidly deployable military networks). The 'infrastructure' in this case may take various shapes, varying from adding powerful base stations, to adding mere wires between static ad hoc nodes. We have formulated versions of this problem as a small world problem, in which short cuts are added to a wireless network to decrease the average path length (or degrees of separation). Our preliminary results show that adding only a few wires or base stations (~1.5% of the nodes) can decrease the average path length by 50%. Of course there are other considerations than the average path length, such as the aggregate capacity, throughput, congestion in the network, among others. We shall investigate these metrics and others in our proposed research. A related problem is placement of these base stations or short cuts. Our analysis shows that the placement need not be random (as suggested by the small world theory). Rather, the short cuts can have limited distances (~20% of the network diameter) and still achieve maximum reduction in average path length. We propose to research these questions in depth in the continuation of this project.

In addition, we propose to study the relationship between security associations and small worlds. We hope this facilitates the establishment of a 'trust' framework for users in the integrated wired-wireless network. We have already started establishing a framework for trust routing and misbehavior isolation in wireless networks (discussed below in more detail). Our initial results indicate that existence of misbehavior affects route validity (i.e., nodes not willing to cooperate by forwarding packets to other users in an ad hoc network 'infect' otherwise valid routes). Route infection of about 90% can be reached with less than 20% non-cooperative nodes, drastically reducing the overall network throughput. Hence, it is essential to develop mechanisms for identifying and isolating misbehavior in ad hoc networks.

Security and Trust routing

We plan to use the small world model for analyzing performance aspects of the heterogeneous wired-wireless networks. In addition we plan to use *small worlds of trust* to design security models for wireless networks. We leverage existing work on cryptography and security keys to build our framework. More specifically we plan to pursue the following research directions.

- *Routing on Trust tables*: Instead of relying on the conventional routing tables (i.e., connectivity tables) routing on trust tables enables a node to differentiate between trustworthy nodes vs. misbehaving or malicious nodes. The trust tables are populated based on measurements of delivered packets. Using these tables a node avoids routing through (or accepting packets from) misbehaving nodes (those that participate in routing protocols but do not forward packets). This scheme encourages cooperation between nodes and punishes 'free riders'; those nodes that want other nodes to forward their packets but they do not want to spend their own energy forwarding other nodes' packets. Details of adapting trust values based on measurements are part of on-going research.

- *Identification and isolation of misbehaving nodes*: Merely measuring packet delivery is not sufficient to identify the misbehaving nodes. Probing protocols for discovering misbehaving nodes are being developed and compared as part of this research effort. Existing approaches based on binary search or expanding ring search incur significant overhead and delays. We are developing '*one-shot*' algorithms to efficiently identify misbehaving nodes.

- *Cheat-proofing*: To address issues of collusion we shall design protocols based on *reputation* reports, where a node does not rely on reports from a specific group of nodes but requests reports from a randomized group of nodes. In addition, correlation between reported data may be used to further verify the data. For example, reports on node locations (in geographic routing) from neighboring nodes may indicate that a node is reporting a false location. We plan to evaluate the efficacy of these approaches in preventing collusion.

- *Secure locations for static wireless and sensor networks:* In location-aware networks (e.g., those using geographic routing), routing may be based on locations. For static, non-mobile, networks it may be more efficient and more scalable to maintain trust tables based on locations instead of node IDs. To route around the malicious nodes (or locations) we introduce a variant of geographic routing that routes through *secure locations*. Our algorithm includes *detour* points in the packet header that avoid the non-secure locations. In addition, the recently introduced *trajectory based routing* schemes will be investigated as an alternative to geographic routing in the above scenarios.

Studies on Micro-Mobility:

As we have shown, the performance of micro-mobility protocols varies widely depending on the handoff scenario (sometimes dictated by the underlying technology) and the choice of protocol parameters. This wide variation of performance may adversely affect the layers that use micro-mobility (e.g., transport). It remains to be seen how the performance discrepancy at the network layer 'ripples' up the protocol stack. We plan to conduct detailed evaluation and analysis of the performance transport protocols (e.g., TCP) over various micro-mobility protocols.

In addition, due to the variety of recently-proposed micro-mobility protocols, there is a need for a rich 'building-block' framework that classifies (and hopefully unifies) studies of micro-mobility protocols. Such framework facilitates to systematically and automatically investigate design alternatives for efficient handoff schemes for various underlying technologies and scenarios.

Another, longer term, plan is to consider application level (i.e., peer-to-peer) multicast for providing efficient micro-mobility. Currently the M&M architecture requires IP-multicast. This restricts the deployment of M&M to domains that support IP-multicast. Through application level multicast we gain significant deployment flexibility and power to tailor multicast mechanisms to the needs of micro-mobility. This might come at the cost of somewhat degraded performance (since the routes may not be optimized), but we believe it provides a more feasible solution. We propose to design and evaluate application-level multicast based micro mobility.

On Mobility Modeling:

The significance of understanding mobility and its effects on wireless networking protocols has been clearly demonstrated through our previous work. Even though we have studied a rich set of mobility models and scenarios, we still plan to enrich our mobility models and scenarios in several aspects.

- Whole city hybrid models: current models include artificial boundaries due to the limited simulation area. These boundaries, we suspect, affect the long-term statistics of the mobility models (e.g., link and path durations). For example, in scenarios spanning cities and highways there can be cases where path duration remains for extended periods of time (for example between groups of users that share similar living and work place neighborhood, etc.). Of course, in such cities, multiple (as opposed to single) mobility models are expected to exist, depending on the node's location on the map (highway vs. street vs. pedestrian vs. convention). Hence, we propose to study hybrid mobility models. More fundamentally, the exponential distributions that we observed in our previous work may become invalid with heavier tails appearing for the path duration distribution in city-wide simulations. We intend to investigate this problem through extensive simulations.

- Exploiting mobility to enhance capacity: some recent protocols (e.g., *EASE*, *FRESH*) have been proposed to take advantage of mobility to increase network capacity or to locate mobile nodes. Such studies have been conducted under certain stringent assumptions, including random mobility (which allows for high probability of direct encounters), high storage capability (in terms of creating table entry for every node in the network), and tolerance to high delays. We plan to investigate variations to those protocols to improve their performance as follows. First, we plan to evaluate the performance of these protocols under a rich set of mobility models. We suspect that these protocols' performance will degrade drastically with high correlation of node movement (i.e., reduced probability of direct encounters), as in group or highway mobility models. Second, we plan to extend the information exchange to include levels of encounters. This helps decrease the degrees of separation and increases the probability of finding a target with less number of direct encounters, hence reducing the overall delay of the system (and warm-up time) drastically. This lends itself to a variant of the small world problem discussed above. Third, we plan to introduce the notion of the probability (*Pi*) of information exchange and storage for each encounter level *i*, which allows us to control the amount of storage required in the nodes. We suspect a trade-off between the amount of storage required and the probability of finding a target node. However, we also suspect that using clustering and short cuts (to create small world like associations) will provide very good performance with a fraction of the storage. We propose to investigate the space of encounter levels, and the probability of storage for each level (*Pi*), and its effect on performance (in terms of success rate, delays and overhead).

- Another possible direction includes collecting traces of real mobility, using for example student mobility on campus. This may be achieved through wireless classrooms, where students carry hand-held devices equipped with GPS that log the locations and times of the device. These traces will give us real samples that may be analyzed using the *IMPORTANT* framework we proposed in our previous work. This will provide greater insight to the validity of the existing mobility models.

Use of the Radio Resource Measurement (RRM) in Ad Hoc Networks:

The Radio Resource Measurement (RRM) work on 802.11k enables measurements at the physical and MAC layers to be available to higher layers. Information about the channel condition, signal strength, signal quality, data rate and load can (and in fact should) significantly improve decisions made at the routing and transport layers. We plan to investigate various ways in which these measurements can be integrated into the protocols designed in this project. Following are some concrete ideas we plan to investigate.

- (1) *Multicast-based Mobility*: For the multicast-based mobility, the measurements from the mobile node to the Access Point (AP) may be used to trigger the CARSet mechanism (in order for nearby APs to join the group) prior to the actual handoff. This reduces the overhead of the mechanism drastically by reducing the join time for the base stations in the CARSet while maintaining the benefits of multicast-based micro mobility.

- (2) *Contact Selection*: The RRM measurements can be used during contact selection (during the query resolution and resource discovery phases) to achieve *load-sensitive* contact selection. The RRM information (regarding the physical and MAC layers) can be piggybacked on the link state information exchanged within the zone. The border and contact selection rules shall use a metric that is comprised of the RRM information in addition to the routing and connectivity information. This leads to selection of better-connected contacts and higher quality routes.

- (3) *Path Duration Analysis*: For path characterization (under various mobility models) we currently define a link to be either 'up' or 'down'. Further extension of the work can investigate associating a richer metric for the link duration based on the RRM measurements. The information collected using the wireless classroom experiments can now include data rate, RSSI, signal quality, and other parameters that facilitate the analysis of path 'stability' and 'quality' as opposed to just 'path duration'.

- (4) *Shortcuts in Heterogeneous Wired/wireless Networks*: our research currently investigates adding short cuts (in terms of links or base stations) to reduce the average path length. The RRM measurements allow us to assess the load on the base stations (or short cuts) and hence develop schemes for load balancing, to manage the resource of the ad hoc network (and the heterogeneous network) more efficiently. This reflects on the routing protocol used. Simple geographic routing (i.e., using the distance to the destination as the only metric for routing) does not take the link quality or load into account. Developing routing protocols that take load into account is a promising direction to investigate.

Implementations and Demos:

As part of our plan, we are in the process of setting up a test bed to implement and demonstrate some of the above technologies. The USC EE wireless networking laboratory (that is founded and directed by the PI A. Helmy) currently includes three 802.11 base stations and various laptops, handhelds and pocket PCs. Experimentation for handoff (currently using MIPv6) are already in place, in addition to a small ad hoc network. The current test-bed, however, is small scale (5-20 nodes). Current plans include the possible extension of the test bed, and implementation of the contact-based mechanisms for efficient resource discovery and query resolution in wireless networks. Furthermore, we are investigating the implementation of a proof-of-concept network to illustrate the integrated heterogeneous wired-wireless network.

Personnel Involved in Research

Ph.D. students/Research assistants: Karim Seada (*RR*), Fan Bai (*IMPORTANT*, *PATHS*), Shao-Cheng Wang (Small transfers), Ganesha Bhaskara (*M&M*)

Collaborators: Bhaskar Krishnamachari, Narayanan Sadagopan (*ACQUIRE*, *PATHS*), Ramesh Govindan (Location errors effect on face routing), Sandeep Gupta, Muhammad Jaseemuddin (*M&M*)