# Research Statement

Sanjit Krishnan Kaul
**sanjit@winlab.rutgers.edu**
`www.winlab.rutgers.edu/~sanjit`

## Research Brief and Philosophy

My dissertation research contributes to wireless medium access control (MAC) and modeling of wireless channels in vehicular networks. I have also worked on enabling emulation on wireless testbeds, and last but not the least, acquired experience in design and development of wireless systems.

Enabling on-road safety requires reliable and timely broadcast of time-varying state information amongst vehicles, hundreds of which may be in communication range. Large networks and high state messaging rates make broadcasting reliably a challenging problem. The reliable achievable rate by any transmitter is limited by its worst channel. I explore schemes [1, 2] that allow vehicles to relay the information of other vehicles while minimizing the average age of information at vehicles in the network.

IEEE 802.11p proposes carrier sense based medium access techniques for vehicular networks. Such access in presence of large number of roads and high offered loads leads to high unreliability due to packet collisions. I have worked on allowing safety applications, using a CSMA MAC, to achieve messaging rate that minimizes age of information at all vehicles [3]. Other schemes that improve reliability include reducing the application information rate by allowing for prediction and benefiting from spatial diversity [4, 5].

Knowledge of the underlying wireless channel is of importance in designing a communication system. In my work I have contributed to measurement and modeling of the vehicle to vehicle channel (power measurements) with up to 6 vehicles in vicinity, with the maximum distance between the transmitter and receiver about 50m. The aim is to provide fairly simple models that can be used to evaluate communication schemes between vehicles. An earlier contribution quantified the effect of antenna placement on a car on measurements of packet error rate (PER) and received signal strength indicator (RSSI), using off-the-shelf Atheros radios [6, 7, 8].

The past decade has witnessed greater emphasis on emulation in the networking research community. In addition to theory and simulation stress is on real world evaluations using prototypes of the envisioned system. The availability of cheap off-the-shelf radios and the ability to program them almost entirely in software, and testbeds like ORBIT and Planet Lab make emulation feasible. I worked on methods [9, 10, 11] by which users could map real-world topologies with mobile nodes on ORBIT[1], which has static nodes and a static propagation environment.

Before enrolling in graduate school I worked on designing and developing software for WCDMA networks (at UE and RNC). Contributions include the Radio Resource Control layer at the UE and the RNC, a geographical redundancy solution and a subscriber management system for a Home Location Register (HLR).

The years at WINLAB[2] (Rutgers University) and prior to that in the industry have helped me gain proficiency in wireless system analysis, design and development. A sound foundation in theory and experience with real-world systems, I have the skills to partake in a wireless system from initial conception to final deployment. I like to approach a problem using a multi-pronged approach, including theoretical analysis and modeling, empirical study, simulation and, when feasible, a quick prototype implementation and real-world evaluation. Given the role it continues to play in my research, I cannot overstate the importance of the right collaboration. I like to keep my research relevant to real world requirements. However, I also like to look at problems in greater generality than a specific real application may require. I believe, the insights gained via such a quest are most often valuable.

Next, I describe my research in detail and follow it up with a research agenda.

## Research Projects Grouped by Area

**Messaging In Vehicular Networks:** Networks of on-road vehicles are an example of ad-hoc networks that are expected to enable a broad spectrum of applications including that of public safety, traffic management and assistance, driver comfort and infotainment. Applications, for example lane change assistance, will provide drivers with information to make safe maneuvers and greater time to react to on-road events. *My research contributes to enabling messaging between vehicles to enable on-road safety.* Safety applications require vehicles to periodically broadcast their time-varying state, for example location, possibly as often as 10 times a second, to other vehicles

[1] `www.orbit-lab.org`
[2] Wireless Information Network Laboratory

that maybe hundreds of meters away. At each vehicle, the state information of other vehicles must satisfy stringent delay constraints, typically, must not be older than the broadcast period. **The research challenge is designing delay optimal mechanisms that allow a wireless network of $N$ arbitrarily connected nodes to exchange their time varying state information**. We want to minimize the system delay, i.e., that is the average delay suffered by nodes in their knowledge of other nodes' information (states). Approaches I have worked on follow.

*Delay Optimal State Dissemination with Piggybacking [1, 2]:* The reliable rate achievable by any broadcasting transmitter is limited by its worst channel. For large networks, together with the fact that large transmit powers lead to interference in networks in proximity, relaying is an interesting alternative. Safety messaging involves packets with large overheads like authentication and much smaller state information, like location co-ordinates. For such packets we assume that node transmissions can piggyback other nodes' state information with negligible increase in their packet transmission times. The optimization problem is to find round robin schedules that minimize the system delay. It turns out that piggybacking is not a fix for unreliable messaging, it is no better than message repetition for large networks. Instead, its purpose is to convey the state of a node beyond its coverage. We explore schedules over arbitrary graphs. An optimal algorithm, of time complexity $O(N)$, for any tree-graph is proposed and its optimality proven, and gains shown for example networks. Extending the problem to explicitly account for the bandwidth (transmission time) utilized by piggybacking, surprisingly leaves the objective function unchanged, though the optimal solution changes. Possible extensions for the future are looking at optimal schedules when the nodes benefit from spatial reuse, optimal schedules for a general graph and investigating the interplay between optimal ordering of nodes and the number of other nodes' information they piggyback.

*Minimizing Age of Information in Congested Vehicular Networks [3]:* Even in congested networks, when applications may not be able to achieve very high messaging rates, on-road vehicles must be able to converge to the best possible messaging rate, a rate that minimizes the average age (delay) of vehicles' information at any vehicle in the network. Using simulations of large vehicular networks (hundreds of vehicles in communication range of each other) we show that setting the contention window size to the optimal derived by Bianchi, for saturated traffic flows, does not achieve the minimum system delay for a congested network with a finite non-zero queue size. The system delay is shown to have a unique minimum *over messaging rates of interest* and a distributed application rate-control algorithm that achieves the minimum is designed and implemented. The convergence of the proposed algorithm was tested via simulation and a prototype was tested on the ORBIT grid, using 300 nodes. Possible extensions include investigating the case when different nodes may assume different messaging rates. For example, a vehicle whose state changes slowly may broadcast at a lesser rate than a fast moving vehicle.

*On Predicting and Compressing Vehicular GPS Traces [4]:* One approach to alleviate congestion in large vehicular networks is to reduce the frequency of location update messages when the movements of a vehicle can be predicted by nearby vehicles. We empirically study savings in messaging from predicting vehicular locations, given a Global Positioning System trace of a vehicles recent path. The performance of linear and higher degree polynomial prediction algorithms using about 2500 vehicle traces collected under urban and highway driving conditions is evaluated. Linear Polynomial Prediction gave the maximum prediction savings. With the savings, a location update rate of 1Hz sufficed for vehicles under city driving conditions.

*Geo-Backoff based Co-operative MAC for V2V networks [5]:* We design and implement GeoMAC, a MAC protocol that exploits spatial diversity in highly mobile wireless networks. It achieves message delivery with low average latency, limited jitter, and high reliability when compared to other known mechanisms like AODV and GPSR over 802.11 MAC with retries. Conventional MAC layers address reliability through ARQ mechanisms that retransmit messages from the source, if earlier transmissions were not acknowledged. These schemes essentially exploit temporal diversity since retransmissions are only likely to succeed if the channel has improved. GeoMAC exploits spatial diversity, by allowing other nearby nodes to opportunistically forward and retransmit messages. A geo-backoff mechanism uses geographic distance to the destination as a heuristic to select the forwarder most likely to succeed. The mechanism does not require nodes to monitor channel state or position of their neighbors, except for approximate node density, thus enabling their use in highly mobile networks with low coordination overhead.

**Vehicular Channel Modeling** [6, 7, 8]: The vehicle-to-vehicle (V2V) wireless propagation channel is different from the often studied cellular channels in that it involves transmit and receive antennas of similar heights that are a few meters above the ground. The physical environment consists of large scatterers (vehicles) well within the near field of each other. Also, the scattering environment is time varying. Last but not the least, antenna placement on a vehicle, and a vehicle's geometry can effect the channel between the vehicle and other vehicles.

*Vehicle-to-Vehicle Channel Modeling with Cars in Vicinity [6]:* We measure the channel between two cars, one transmitting a sinusoid at 5.5Ghz[3] while the other receives it using a spectrum analyzer and calculates the received power. The transmit and receive antennas are placed at the cars' roof centers. Specifically, we want to measure the effect of the physical presence of other cars in vicinity of the transmitter and receiver. Measurement scenarios are designed to capture typical multi-lane traffic movement patterns (for example lane-changes, car(s) in adjacent lane, car(s) in front). All measurements were carried out in a vacant parking lot, which allowed for a repeatable

[3]The 5Ghz band is of interest for planned inter-vehicle communication standards

and controlled setting. Also, the lack of any large scatterers like buildings in the vicinity helped capture in isolation the effect of cars in vicinity. We consider transmitter receiver separation of up to 50m and up to four other cars in vicinity. Sets of measurements that captured typical multi-lane vehicle movement patterns were made. A multi-sinusoid model (two to four sinusoids) is used to model the channels measured. The model emulates well the Bit Error Rate performance of the communication system.

*Effect of Antenna Placement and Cars on Vehicle-to-Vehicle Communication Links [7, 8]:* We examine empirically the effects of antenna placement and a car's geometry on vehicle-to-vehicle link performance, specifically signal strength and packet error rate. The experiments use roof- and in-vehicle mounted omni-directional antennas connected to IEEE 802.11a radios operating in the 5GHz band. The effects are quantified in environments with and without a *line of sight* between the transmitter and receiver. The corresponding effect on network performance is shown via simulation. Antenna diversity can alleviate the effects of car geometry, however. The insights obtained are especially useful to those who evaluate network and/or MAC protocol performance in vehicle networks using real world setups. They also help create more accurate simulation models.

**Emulation Testbeds** [9, 10, 11]: A key challenge in conducting mobile networking experiments is evaluating medium access control and network layer protocols over a broad range of network topologies and wireless channel characteristics. I contributed to a wireless network emulation mechanism using noise injection on the ORBIT testbed (800 radio grid in a space of 20m x 20m). Given a description of the desired network, a set of arbitrarily placed wireless testbed nodes and a set of relatively simple additive white gaussian noise generators, the system will select a subset of the testbed nodes and configure noise power on the interference generators to emulate the desired network on the testbed. While the procedure cannot map any arbitrary wireless configuration onto a testbed, relaxing the mapping requirements to topologies with equivalent MAC layer performance characteristics increases the feasibility of mapping a broad range of topologies. I also contributed to the design and development of a mobility emulation framework, which emulated mobility on the ORBIT grid by mapping a mobile node to different static ORBIT nodes in time. The state of the mobile node was replicated across the mapped nodes in time.

## Research Agenda

Consumer wireless networks have been around for more than two decades. However, barring the recent proliferation of WiFi devices, most of these networks are cellular networks. The nodes in the networks are homogeneous in the wireless technologies they use and limited in the applications they support. Today, we live amongst a hitherto unseen proliferation of heterogeneous applications, each providing the end user with a unique service or experience. Applications may range from the critical, e.g., delivering healthcare or, safety messaging in vehicular networks, to seamless connectivity amongst devices at home. While vehicular networks contain nodes, akin to those in WiFi, optimized to provide delay optimal beaconing, home networks will achieve high data rates benefiting from large available bandwidth in the 60Ghz band. A future containing a multitude of ad-hoc networks, each optimized to serve its unique set of user applications beckons.

An ubiquitous wireless can bring to life many enriching and exciting possibilities. A top-down approach starting with investigation into the specific requirements of applications, study of the unique characteristics of deployment of networks that will support them, and accordingly selecting a radio technology, designing access control, relaying and/or routing protocols will hold the key. Modeling of the wireless environments, designing access control and messaging strategies (e.g., broadcast and/or relaying) fall within the general area of my expertise. I have prototyped systems and orchestrated performance measurements of real-world systems [6, 7, 8, 12], an experience that will help me deploy designed systems in the real world. Next, I describe challenges, which are within the realm of my expertise, specific to a few chosen applications for whom many contend that there exists a market opportunity.

*"Towards Hands-off, feet-off, brains-off" driving*: A world where vehicles drive themselves, with occupants safely ensconced, is the holy grail of intelligent transportation systems. Such a system consists of a large number of vehicles exchanging time-critical messages that help them choose maneuvers, at least warn drivers of on-road events in a timely manner. The use of the wireless medium to ensure reliable information transfer in a network within finite time is a challenge and is unlike the typical use case for a wireless system, where delay can be traded for reliability.

Single-hop reliable broadcasting over a large network of cars may require prohibitively large amounts of transmit power and may cause undesirable interference in adjacent road networks. Too many hops to disseminate information between vehicles in a network may lead to large delays. Studies, theory and simulation based, are required to design schemes that select the right trade-off between power and spatial reuse. The selected trade-off must minimize the delay in dissemination of critical information. Such a study will also help choose the right kind of communication system. For example, if small orthogonal cells of vehicles using relaying is the optimal solution, then physical layer technologies like 60GHz and Light Based communication may be more useful as by nature they allow greater spatial reuse. Alternatives to 802.11 systems, for example polling based MAC schemes, and low overhead ACK mechanisms for broadcast applications need exploring. Last but not the least, the measurement and modeling of correlation of channels between different transmitter and receiver cars in a network, for example on a freeway, are of interest and will help design schemes that benefit from the abundant spatial diversity in vehicular networks.

*Home Wireless*: The ecosystem of devices at home thrives on inter-device communication, for example cameras and phones may *talk* to the home desktop, which in turn may *talk* to a large display. The wire though is currently irreplaceable due to the limited data rates supported by wireless. The availability of 7Ghz of unlicensed spectrum at 60Ghz may finally change that. However, the frequency band suffers from absorption by Oxygen. The expensiveness of producing power at large frequencies and the ease of beamforming at the millimeter wavelengths has lead to beamforming being the chosen way to alleviate absorption losses. The resulting thin beams can be easily blocked, however. Challenges include designing a *link layer that will rely heavily on relaying*. Also, beamforming causes *deafness*, i.e., the inability of carrier sense to detect transmissions of all nodes in physical vicinity. Alternatives like reserving the data channel using out-of-band signaling using existing technologies like 802.11 need exploring. Chosen schemes must be studied to reveal the trade-off between the added costs and improvements in achieved data rates. Modeling of the propagation characteristics of millimeter waves in a typical home environment should give more insights into the achievable rates in home networks and schemes feasible at the MAC and PHY layer.

*Healthcare Everywhere*: Wireless networks can make possible medical monitoring, diagnosis and delivery of care any time and place. The network consists of tiny low-power sensors, which measure vitals of a patient and periodically send the data for diagnosis to a medical facility. The diagnostic facility can send back commands that lead to delivery of medicine to the patient. The sensors connected to the body form a *Body Area Network* and connect using wireless to a node that routes the information to its destination (medical facility). Wireless enables both patient and doctor mobility while keeping the care at desired levels. One challenge is to design networks that *support reliable periodic messaging over links that minimize network outage*. Diversity mechanisms, say hand-off to another network, possibly using a different technology, may need to kick in when the body sensors loose coverage of the network they are connected to. Also, the sensors connected to the body are low-power, battery limited, and are expected to do little or no processing. The data rates required may vary from very small to significant (e.g., video). A significant challenge is to design messaging to ensure the *privacy of the patient*, that is the patient's information must not be decipherable by any other than the authorized medical personnel.

## Publications


[1] S. K. Kaul, R. Yates, M. Gruteser, and J. Fukuyama, "Delay optimal state dissemination with piggybacking," **Preparing for Submission**, 2011.

[2] ——, "Delay optimal state dissemination with piggybacking (Extended - accounting for bandwidth used)," **Preparing for Submission**, 2011.

[3] S. Kaul, M. Gruteser, V. Rai, and J. Kenney, "Minimizing age of information in congested vehicular networks," in *IEEE Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, **Submitted**, 2011.

[4] ——, "On predicting and compressing vehicular GPS traces," in *Communications Workshops (ICC), 2010 IEEE International Conference on*, 2010, pp. 1–5. [Online]. Available: 10.1109/ICCW.2010.5503947

[5] S. Kaul, M. Gruteser, R. Onishi, R. Vuyyuru, and T. I. T. Center, "GeoMAC: Geo-Backoff based co-operative MAC for V2V networks," in *IEEE International Conference on Vehicular Electronics and Safety, 2008. ICVES 2008*, 2008, pp. 334–339.

[6] S. Kaul, L. Greenstein, and M. Gruteser, "Vehicle-to-Vehicle channel modeling with cars in vicinity," **Preparing for Submission**, 2011.

[7] S. Oh, S. Kaul, and M. Gruteser, "Exploiting vertical diversity in vehicular channel environments," in *Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium on*, 2009, pp. 958–962.

[8] S. Kaul, K. Ramachandran, P. Shankar, S. Oh, M. Gruteser, I. Seskar, and T. Nadeem, "Effect of antenna placement and diversity on vehicular network communications," in *IEEE Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, 2007, pp. 112–121.

[9] S. K. Kaul, M. Gruteser, and I. Seskar, "Creating wireless multi-hop topologies on Space-Constrained indoor testbeds through noise injection," in *IEEE Tridentcom*, Mar. 2006.

[10] K. Ramachandran, S. Kaul, S. Mathur, M. Gruteser, and I. Seskar, "Towards large-scale mobile network emulation through spatial switching on a wireless grid," in *Proceedings of the 2005 ACM SIGCOMM workshop*. Philadelphia, Pennsylvania, USA: ACM, 2005, pp. 46–51.

[11] ——, "Mobility emulation through spatial switching on a wireless grid (Demo)," in *MobiSys 2005*. Philadelphia, Pennsylvania, USA: ACM, 2005.

[12] S. Mathur, S. Kaul, M. Gruteser, and W. Trappe, "ParkNet," in *Proceedings of the 2009 MobiHoc S3 workshop on MobiHoc S3 - MobiHoc S3 '09*, New Orleans, Louisiana, USA, 2009, p. 25.