Collection on Mobile Ad Hoc Networks

by

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Foreword

This collection compiles most, if not all, of papers on mobile ad hoc networks from the following journals and proceedings, and categorize them. The introduction for each paper is simply extracted from its abstract.

- IEEE Transactions on Vehicular Technology, 2002 - 2003
- IEEE Transactions on Wireless Communications, 2002 - vol. 3, no. 1, Jan. 2004
- IEEE Journal on Selected Areas in Communications, 2002 - 2003
- IEEE Communications Magazine, 2002 - 2003
- IEEE Communications Letters, 2002 - 2003
- IEEE Wireless Communications, 2002 - 2003
- IEEE Transactions on Parallel and Distributed Systems, 2002 - 2003
- Proceedings of IEEE, 2002 - vol. 92, no. 2, Feb. 2004
- IEEE Transactions on Consumer Electronics, 2002 - 2003
- Electronics Letters, 2002 - 2003
- IEEE Transactions on Computers, 2002 - 2003
- IEEE/ACM Transactions on Networking, 2002 - 2003
- Computer, 2002 - vol. 37, no. 2, Feb. 2004
- IEEE Internet Computing, 2002 - vol. 8, no. 1, Jan.-Feb. 2004
• Wireless Networks, 2002 - vol. 10, no. 1, Jan. 2004
• Wireless Communications and Mobile Computing, 2002 - vol. 4, no. 1, Feb. 2004

• IEEE International Symposium on Information Theory, 2002 - 2003
• IEEE Information Theory Workshop, 2002 - 2003
• IEEE Wireless Communications and Networking, 2003
• IEEE International Conference on Communications, 2003
• IEEE Global Telecommunications Conference, 2003
• International Conference on Mobile Computing and Networking, 2003
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Chapter 1

Overview

• A brief overview of ad hoc networks: challenges and directions [1]
  Ramanathan and Redi presented history, open problems and the future of ad hoc networks in it.

• Multicast over wireless mobile ad hoc networks: present and future directions [2]
  Due to the very diverse requirements of the applications and the unpredictable nature of ad hoc networks, it is necessary to investigate and discern the applicability of existing ad hoc multicast protocols and quantify which is more suitable for which type of application. Cordeiro et al provided a detailed description and comparison of multicast protocols for application developers in selecting an appropriate multicast protocol for applications like multiplayer online gaming, where players residing at different locations participate in the same gaming session through their handheld portable devices.

• Sensor networks: an overview [3]
  Advances in hardware and wireless network technologies have created low-cost, low-power, multifunctional miniature sensor devices. These devices make up hundreds or thousands of ad hoc tiny sensor nodes spread across a geographical area. Tubaishat and Madria depicted examples of possible applications, a hierarchical example, challenges, requirements, potential advantages, operation, data-centric, aggregation and dissemination of sensor networks.

• Sensor networks: evolution, opportunities, and challenges [4]
  Chong and Kumar traced the history of research in sensor networks over the past three decades, including two important programs of the Defense Advanced Research Projects Agency (DARPA) spanning this period: the Distributed Sensor Networks (DSN) and the Sensor Information Technology (SensIT) programs. Technology trends that impacted the development of sensor networks were reviewed, and new applications such as infrastruc-
ture security, habitat monitoring, and traffic control were presented. Technical challenges in sensor network development included network discovery, control and routing, collaborative signal and information processing, tasking and querying, and security. The paper was concluded by presenting some recent research results in sensor network algorithms, including localized algorithms and directed diffusion, distributed tracking in wireless ad hoc networks, and distributed classification using local agents.

- Ad hoc networks [5]
  Wu and Stojmenovic reviewed potential solutions to problems encountered in ad hoc networks including topology control, data communication, and service access.

- Real-time communication and coordination in embedded sensor networks [6]
  Sensor networks can be considered distributed computing platforms with many severe constraints, including limited CPU speed, memory size, power, and bandwidth. Stankovic et al. first discussed the state of the art with respect to general research challenges, then focused on more specific research challenges that appeared in the networking, operating system, and middleware layers. For some of the research challenges, initial solutions or approaches were identified.

- Group communications in mobile ad hoc networks [7]
  Mohapatra et al. explored several potential solutions to the unique problems of wireless mobile communications, which have variable and unpredictable characteristics due to mobility and signal strength fluctuations with respect to time and environment.

- Decentralized software distribution for SDR terminals [8]
  Dillinger and Becher described a novel approach to downloading software in mobile networks. The motivation for a decentralized approach was to cut down the overall download time for all relevant terminals, thereby considering not just over-the-air distribution of software. In particular, the authors considered terminal-to-terminal upgrades, which must be realized in ad hoc networks or HIPERLAN/2, where a direct mode between terminals could be established. The concept could also be contemplated for base-station-centric networks. For a client-to-client upgrade new security problems were to be resolved, and a suitable security concept was described. The security concept was independent of the network; that is, even in fixed networks a similar concept could be conceived. Basically, the decentralized concept was not restricted to mobile networks, but the procedures described are mobile-centric.

- Wireless community networks [9]
  An open standard IEEE 802.11 wireless local area networking technology provides an inexpensive and easy way to share bandwidth among multiple users. Such technology
makes it possible to implement ad hoc wireless community networks using fixed wireless nodes rather than conventional base. A rural ad hoc network forwards packets from one wireless node to another to route data to a limited number of Internet gateways. A wireless community network uses two types of links between nodes. Point-to-multipoint links use omnidirectional antennas, while point-to-point links employ unidirectional antennas.

• Algorithmic, geometric and graphs issues in wireless networks [10]
Li presented an overview of the recent progress of applying computational geometry techniques to solve some questions, such as topology construction and broadcasting, in wireless ad hoc networks. Treating each wireless device as a node in a two-dimensional plane, the author modeled the wireless networks by unit disk graphs in which two nodes were connected if their Euclidean distance was no more than one. The author first summarized the current status of constructing sparse spanners for unit disk graphs with various combinations of the following properties: bounded stretch factor, bounded node degree, planar, and bounded total edges weight (compared with the minimum spanning tree). Instead of constructing subgraphs by removing links, the author then reviewed the algorithms for constructing a sparse backbone (connected dominating set), that is, subgraph from the subset of nodes. The author then reviewed some efficient methods for broadcasting and multicasting with theoretic guaranteed performance.

• Ad hoc networks: not an ad hoc field anymore [11]
The genesis and growth of the field of ad hoc wireless networks is put into perspective through a brief review of historical highlights and through a focused discussion of some of the fundamental traits of such networks.

• Supporting multicasting in mobile ad-hoc wireless networks: issues, challenges, and current protocols [12]
The basic philosophy of personal communication services is to provide user-to-user, location independent communication services. The emerging group communication wireless applications, such as multipoint data dissemination and multiparty conferencing tools have made the design and development of efficient multicast techniques in mobile ad-hoc networking environments a necessity and not just a desire. Multicast protocols in mobile ad-hoc networks have been an area of active research for the past couple of years. Papavassiliou and An summarized the activities and recent advances in this work-in-progress area by identifying the main issues and challenges that multicast protocols were facing in mobile ad-hoc networking environments, and by surveying several existing multicasting protocols. The authors presented a classification of the current multicast protocols, discussed the functionality of the individual existing protocols, and provided a qualitative comparison of their characteristics according to several distinct features and performance.
parameters. Furthermore, since many of the additional issues and constraints associated with the mobile ad-hoc networks were due, to a large extent, to the attribute of user mobility, the authors also presented an overview of research and development efforts in the area of group mobility modeling in mobile ad-hoc networks.
Chapter 2

Routing

• Information-theoretic lower bounds on the routing overhead in mobile ad-hoc networks [13]
Zhou and Abouzeid sought to derive a universal curve against which we could measure how good (or bad) a variable topology routing protocol (e.g. for ad-hoc networks) performed, in comparison with a theoretical minimum routing overhead, which was the amount of information needed to describe the changes in a dynamic network topology.

• Multi-rate aware routing protocol for mobile ad hoc networks [14]
Seok et al. introduced multi-rate aware routing scheme that helped to improve the resource utilization and to minimize the power consumption in mobile ad hoc networks (MANET). The authors proposed a Multi-rate aware sub layer (MAS) which was independent of IP protocol and enabled the full utilization of the multi-rate channel characteristics. The key function of MAS was to change its next hop node to another node through which higher data rates were available, in the basis of two-hop neighbor information and link states. We showed through simulation that multi-rate aware routing protocol outperformed traditional MANET routing protocols due to its utilization of multi-rate support (e.g., IEEE 802.11b 11Mbps-1Mbps).

• Load-aware on-demand routing (laor) protocol for mobile ad hoc networks [15]
Song et al. proposed an efficient Delay-based Load-aware On-demand Routing (D-LAOR) protocol, which determined the optimal path based on the estimated total path delay and the hop count. The authors demonstrated the effectiveness of D-LAOR by integrating it with the Ad hoc On-demand Distance Vector (AODV) routing protocol. Simulation results showed that D-LAOR scheme increased packet delivery fraction and decreased end-to-end delay by more than 10% in a moderate network scenario when compared with the original AODV and other LAOR protocols.
• Determining the optimal configuration for the relative distance microdiscovery ad hoc routing protocol [16]

Agglou and Tafazolli analyzed the relative distance microdiscovery (RDM) ad hoc routing (RDMAR) protocol and its individual mechanisms, and determined their effectiveness and the manner in which they interacted in order to contribute to the overall protocol performance. A framework for the modeling and analysis of the RDM algorithm was also presented and, based on this, a method for estimating a nearly optimal RD between two mobiles was then introduced. As demonstrated through simulations, the performance of RDM was very close to this of an optimal route searching policy while the query localization protocol was able to reduce the routing overhead significantly, often in the neighborhood of 48-50% of the flooding-based schemes.

• DEAR: an extension of traffic engineering for routing and resource management in ad hoc wireless networks [17]

Yeh proposed differentiated engineered adaptable routing (DEAR) for quality-of-service (QoS) routing in ad hoc mobile wireless networks. In DEAR, traffic was engineered for both its locations (as in conventional traffic engineering) and its amount according to the proposed demand-engineered QoS routing. Moreover, QoS was provisioned in a differentiated manner through the proposed differentiated QoS routing, and was adaptable to traffic and network conditions through the proposed adaptable QoS routing. The author also developed DEAR STAR (selective table-driven ad hoc routing) and DEAR POWER (power-aware on-demand wireless embedded routing) to enable QoS-guaranteed and power-aware routing in ad hoc networks by utilizing stationary wireless stations and/or through dynamic maintenance of virtual stationary nodes. Finally, the author applied backward learning to QoS routing in ad hoc networks.

• Sensitivity analysis for an optimal routing policy in an ad hoc wireless network [18]

Javidi and Teneketzis examined the sensitivity of optimal routing policies in ad hoc wireless networks with respect to estimation errors in channel quality. The authors considered an ad hoc wireless network where the wireless links from each node to its neighbors were modeled by a probability distribution describing the local broadcast nature of wireless transmissions. These probability distributions were estimated in real-time. The authors investigated the impact of estimation errors on the performance of a set of proposed routing policies.

• QoS-ASR: an adaptive source routing protocol with QoS support in multihop mobile wireless networks [19]

Labiod and Quidelleur proposed a novel routing protocol named QoS adaptive source routing protocol (QoS-ASR). It was an adaptive soft-QoS protocol with aggregate flows.
It applied the source routing mechanism defined by the dynamic source routing (DSR) unicast protocol to avoid channel overhead and to improve scalability. QoS-ASR handled QoS criteria taking into account application requirements (link transmission delay, available bandwidth, packet loss rate) combined with network state related constraints (battery life, link stability, node congestion state). The performance of the proposed scheme was evaluated via simulations and was compared to DSR.

- Extended precomputation based selective probing (PCSP) scheme for QoS routing in ad-hoc networks [20]

Lee et al. extended the recently proposed QoS routing scheme called precomputation based selective probing (PCSP) for the ad-hoc network environment. This PCSP scheme performed advanced selective probing approaches based on precomputed information to find the cost-optimal path taking into account the impreciseness of state information. The precomputed information enabled the set of neighbor nodes involved in the probing process to be strictly limited, thereby reducing the message complexity without sacrificing cost optimality. In the ad-hoc network environment, the authors applied local multicast to reduce message complexity further and adopted a dynamic path maintenance algorithm to support the dynamic nature of ad-hoc networks. Computer simulation revealed that the PCSP scheme indeed exhibited low message complexity and high success rate with guaranteed optimal search in the ad-hoc network environment.

- A Bluetooth scatternet-route structure for multihop ad hoc networks [21]

Bluetooth scatternets, integrating polling, and frequency hopping spread-spectrum in their medium access control protocol, provide a contention-free environment for Bluetooth devices to access the medium and communicate over multihop links. Liu et al. proposed a scatternet-route structure to combine the scatternet formation with on-demand routing, thus eliminating unnecessary link and route maintenances. The authors introduced an extended ID (EID) connectionless broadcast scheme, which, compared with original Bluetooth broadcast mechanism, achieved very much shortened route discovery delay. The authors also proposed to synchronize the piconets along each scatternet route to remove piconet switch overhead and obtain even better channel utilization. Furthermore, the authors presented a route-based scatternet scheduling scheme to enable fair and efficient packet transmissions over scatternet routes. Network performance analysis and simulations showed that scatternet routes could provide multihop wireless channels with high network utilization and extremely stable throughput, being especially useful in the transmission of large batches of packets and real time data in wireless environment.

- A novel approach to source routing for multi-hop ad hoc networks [22]

Papapetrou and Pavlidou presented an efficient routing protocol that combined source
routing, caching of routes, and the use of sequence numbers to alleviate the routing load and at the same time increased the successful delivery of data packets.

- Fault tolerant routing in mobile ad hoc networks [23]
  Designing an effective and efficient fault tolerant routing protocol is inherently hard, because the problem is NP-complete and the precise path information is unavailable. Xue and Nahrstedt solved this problem by presenting an end-to-end estimation-based fault tolerant routing algorithm $E^2FT$. $E^2FT$ deployed two complementary processes: route estimation and route selection. Through end-to-end performance measurement, the route estimation process gave improving estimation results via iterations. Based on these estimation results, the route selection process decided a multipath route for packet delivery. The route selection was refined progressively with the increasingly accurate estimation result using "confirmation" and "dropping" procedures. Through theoretical analysis and simulation, the authors showed $E^2FT$ could achieve a high packet delivery rate with acceptable overhead.

- Adaptive QoS routing based on prediction of local performance in ad hoc networks [24]
  Sun and Hughes proposed an adaptive QoS routing scheme based on the prediction of the local performance in ad hoc networks. It was implemented by a link performance prediction strategy. Integrated QoS performance in each local area was estimated based on translating the effects of the lower layer parameters into the link state information. Corresponding to the prediction approach, several mechanisms were built to complete the location information management process (i.e., information monitoring, collecting and updating functions). The node movement was characterized by the probabilities of the link state and the prediction of local QoS performance. The QoS routing proposed was adaptive to its node’s mobility, and also scalable due to the distributed structure.

- A framework for wireless ad hoc routing protocols [25]
  Lin et al. presented a framework for wireless ad hoc routing protocols based on the concept of a relay node set (RNS). This framework facilitated the comparison, design, and improvement of wireless ad hoc routing protocols. The authors briefly presented an analytical model for comparing protocols using this framework with packet overhead as the metric. They also applied the framework to show how to improve a routing protocol.

- Passive duplicate address detection in mobile ad hoc networks [26]
  Weniger investigated the feasibility of a new Duplicate Address Detection (DAD) approach: the detection of duplicate addresses in a passive way, only by monitoring routing protocol traffic. Based on classic link state routing, three concepts of passive duplicate address detection (PDAD) were proposed. Two link-state protocols currently in discussion in the IETF MANET working group, the fisheye state routing (FSR) protocol and the
optimized link state routing (FSR) protocol and the optimized link state routing protocol (OLSR), were analyzed regarding these concepts.

- A hybrid approach to Internet connectivity for mobile ad hoc networks [27] Ratanchandani and Kravets examined the use of mobile IP in order to provide global Internet connectivity to ad hoc networks that use an on-demand routing protocol. The authors presented a hybrid scheme that used techniques such as TTL scoping of agent advertisements, eavesdropping and caching agent and advertisements to combine the advantages of proactive and reactive approaches to providing connectivity. The simulation results showed that this approach achieved excellent connectivity while keeping overhead costs low.

- Evaluation of ad-hoc routing protocols under a peer-to-peer application [28] Barbosa-e-Oliveira et al. conducted a detailed study of a Gnutella-like application running over a mobile ad-hoc network where three different protocols were considered. The results showed that each of the protocols analyzed performed well in some scenarios for some metrics yet had drawbacks in others.

- A bounding algorithm for the broadcast storm problem in mobile ad hoc networks [29] An efficient broadcasting protocol should be devised to reduce the unnecessary redundant rebroadcasting at some nodes (redundancy) as well as to increase the coverage area as much as possible (reachability). Kim et al. proposed a bounding algorithm, which was known to be an efficient candidate to accommodate the two goals, that was to increase reachability while limiting redundancy.

- Performance comparisons of two on-demand ad hoc routing protocols in dynamic rate shifting WLANs [30] Kown et al. extensively studied the impact of dynamic rate shifting on the performance of ad-hoc routing protocols in various situations in multi-rate WLANs environments. The authors investigated whether the dynamic rate shifting scheme supported by the IEEE 802.11b standard affected the relative performance of the routing protocols being studied. The authors extended the ns-2 network simulator to accurately model the IEEE 802.11b wireless LAN standard, and simulated the performance of two ad hoc routing protocols over each of networks supporting single rate and multi-rate transmissions.

- Localized routing for wireless ad hoc networks [31] Li et al. showed that, given a set of randomly distributed wireless nodes with density $n$, when the transmission range $r_n$ of wireless nodes satisfies $\pi r_n^2 \geq 3^{\log n + c(n)} n$, the localized Delaunay triangulation (LDel) was the same as the Delaunay triangulation with high probability, where $c(n) \to \infty$ as $n$ went infinity. Their experiments showed that
the delivery rates of existing localized routing protocols were increased when localized Delaunay triangulation was used instead of several previously proposed topologies, and the localized routing protocol based on Delaunay triangulation worked well in practice.

- Distributed dominant pruning in ad hoc networks [32]
  Dai and Wu first reviewed a distributed formation of a connected dominating set called marking process and dominating-set-based routing. Then the authors proposed a dominant pruning rule to reduce the size of the dominating set. This dominant pruning rule (called Rule $k$) was a generalization of two existing rules (called Rules 1 and 2). The authors proved that the vertex set derived by applying Rule $k$ was still a connected dominating set. When implemented with local neighborhood information, Rule $k$ was more effective in reducing the dominating set derived from the marking process than the combination of Rule 1 and 2, and had the same communication complexity and less computation complexity. Simulation results confirmed that Rule $k$ outperforms Rules 1 and 2, especially in relatively dense networks with unidirectional links.

- A zone routing protocol for Bluetooth scatternets [33]
  Kapoor and Gerla presented a routing scheme for Bluetooth scatternets, which was based on the zone routing protocol. The authors motivated the design of the routing scheme keeping in mind the specifics of the Bluetooth technology. Simulation results showed that the scheme gave very low overhead while keeping the route acquisition latencies low. The routing information at a node did not require a large amount of storage. In fact, a parameter in the scheme could be varied to trade-off storage information and routing overhead versus route acquisition latency.

- Position-based routing in ad hoc networks [34]
  Routing protocols have two modes: greedy mode (when the forwarding node is able to advance the message toward the destination) and recovery mode (applied until return to greedy mode is possible). Stojmenovic discussed them separately. Methods also differed in metrics used (hop count, power, cost, congestion, etc.), and in past traffic memorization at nodes (memoryless or memorizing past traffic). Salient properties to be emphasized in this review were guaranteed delivery, scalability, and robustness.

- Routing protocol with QoS guarantees for ad-hoc network [35]
  Sheng et al. presented a novel routing protocol for ad-hoc networks, delay sensitive adaptive routing protocol (DSARP), which not only provided a reliable route for delay-sensitive traffic, but also could select the route based on the constrained condition: 'the shortest route and the lowest average delay'. Therefore, the DSARP was assured to provide QoS guarantee and improved the performance of the network. Simulation results
showed that DSARP outperforms the dynamic source routing protocol used in ad-hoc wireless networks.

- Performance enhancements of ad hoc networks with localized route repair [36]
  Duggirala *et al.* proposed and analyzed an on-the-fly strategy that locally repaired the broken route, thereby minimizing the routing overhead. The main motivation behind their Localized Route Repair (LRR) work was to decrease the reaction time of routing protocols, which totally avoided retransmissions. A detailed simulation with MAC layer and physical layer model was used to understand the impact of this mechanism on the performance of routing protocol. An analytical model for the LRR technique was also presented and the results observed to match well with the simulation results.

- Optimisation of route discovery for dynamic source routing in mobile ad hoc networks [37]
  Seet *et al.* proposed a novel technique for optimising the efficiency of route discovery. The optimisation aimed to minimise the number of cached route replies, which was a significant source of overhead for the dynamic source routing protocol. Performance results showed that the overall route discovery overhead could be reduced by more than 30% under high node mobility.

- Bandwidth-efficient routing protocol for mobile ad hoc networks [38]
  Al-Qassas *et al.* proposed and evaluated a new routing protocol, referred to as the vector routing protocol (VRP). One of the main features of the VRP was its lower communication overhead to establish a route from source to destination. Results obtained through simulation experiments revealed that the new VRP algorithm achieved a lower communication overhead than the well known DSDV and AODV protocols, especially in low mobility environments.

- Scalable routing protocols for mobile ad hoc networks [39]
  Hong *et al.* surveyed the routing protocols that addressed scalability. The routing protocols included in the survey fell into three categories: flat routing protocols; hierarchical routing approaches; GPS augmented geographical routing schemes. The authors compared the scalability properties and operational features of the protocols and discussed challenges in future routing protocol designs.

- Configuring BlueStars: multihop scatternet formation for Bluetooth networks [40]
  Petrioli *et al.* described a protocol for the establishment of multihop ad hoc networks based on Bluetooth devices. The protocol proceeded in three phases: device discovery, partitioning of the network into Bluetooth piconets, and interconnection of the piconets into a connected scatternet. The protocol had the following desirable properties: it was
executed at each node with no prior knowledge of the network topology, thus being fully distributed. The selection of the Bluetooth masters was driven by the suitability of a node to be the “best fit” for serving as a master. The generated scatternet was a connected mesh with multiple paths between any pair of nodes, thus achieving robustness. Differently from existing solutions, no extra hardware was required to run the protocol at each node and there was no need for a designated node to start the scatternet formation process.

- A genetic algorithm for shortest path routing problem and the sizing of populations [41]
  Ahn and Ramakrishna presented a genetic algorithmic approach to the shortest path (SP) routing problem. Variable-length chromosomes (strings) and their genes (parameters) were used for encoding the problem. The crossover operation exchanged partial chromosomes (partial routes) at positionally independent crossing sites and the mutation operation maintained the genetic diversity of the population. The proposed algorithm could cure all the infeasible chromosomes with a simple repair function. Crossover and mutation together provided a search capability that results in improved quality of solution and enhanced rate of convergence. The authors also developed a population-sizing equation that facilitated a solution with desired quality. It was based on the gambler ruin model; the equation was further enhanced and generalized. The equation related the size of the population, quality of solution, cardinality of the alphabet, and other parameters of the proposed algorithm. Computer simulations showed that the proposed algorithm exhibited a much better quality of solution (route optimality) and a much higher rate of convergence than other algorithms. The results were relatively independent of problem types for almost all source-destination pairs. Furthermore, simulation studies emphasized the usefulness of the population-sizing equation. The equation scaled to larger networks. It was felt that it could be used for determining an adequate population size in the SP routing problem.

- Extended dominating-set-based routing in ad hoc wireless networks with unidirectional links [42]
  Wu extended dominating-set-based routing to networks with unidirectional links. Specifically, an efficient localized algorithm for determining a dominating and absorbant set of vertices (mobile hosts) was given and this set could be easily updated when the network topology changed dynamically. The derived dominating and absorbant set exhibited good locality properties; that is, the change of a node status (dominating/dominated) affected only the status of nodes in the neighborhood. The notion of dominating and absorbant set could also be applied iteratively on the dominating and absorbant set itself, forming a hierarchy of dominating and absorbant sets. The effectiveness of the approach was confirmed and the locality of node status update was verified through simulation.
Routing and security in mobile ad hoc networks [43]
Milanovic et al. presented four MANET routing algorithms along with a hybrid approach, discussed their advantages and disadvantages, and described security problems inherent in such networks.

Hierarchical routing overhead in mobile ad hoc networks [44]
Sucec and Marsic assessed the scalability, with respect to increasing node count, of hierarchical routing in mobile ad hoc networks (MANETs). The performance metric of interest was the number of control packet transmissions per second per node \( \phi \). To derive an expression for \( \phi \), the components of hierarchical routing that incurred overhead as a result of hierarchical cluster formation and location management were identified. It was shown here that \( \phi \) was only polylogarithmic in the node count.

On route lifetime in multihop mobile ad hoc networks [45]
Tseng et al. presented a formal model to predict the lifetime of a routing path based on the random walk model. Route lifetime was derived based on a probabilistic model. Through such investigation, the authors hoped to provide further insight into issues such as route selection, route maintenance, and network scalability related to MANETs.

Geographic random forwarding (geraf) for ad hoc and sensor networks: multihop performance [46]
Zorzi and Rao proposed a novel forwarding technique based on geographical location of the nodes involved and random selection of the relaying node via contention among receivers. The authors focused on the multihop performance of such a solution, in terms of the average number of hops to reach a destination as a function of the distance and of the average number of available neighbors. An idealized scheme (in which the best relay node is always chosen) was discussed and its performance was evaluated by means of both simulation and analytical techniques. A practical scheme to select one of the best relays was shown to achieve performance very close to that of the ideal case.

Localized delaunay triangulation with application in ad hoc wireless networks [47]
Li et al. presented a novel localized networking protocol that constructed a planar 2.5-spanner of UDG, called the localized Delaunay triangulation (LDEL), as network topology. It contained all edges that were both in the unit-disk graph and the Delaunay triangulation of all nodes. The total communication cost of this networking protocol was \( O(n \log n) \) bits, which was within a constant factor of the optimum to construct any structure in a distributed manner. The experiments showed that the delivery rates of some of the existing localized routing protocols were increased when localized Delaunay triangulation was used instead of several previously proposed topologies. The simulations
also showed that the traveled distance of the packets was significantly less when the FACE routing algorithm was applied on LDEL, rather than applied on GG.

- An ad-hoc routing protocol with minimum contention time and load balancing [48] Kim et al. we proposed an ad-hoc routing protocol with Minimum Contention time and Load Valancing (MCL). MCL had two main characteristics. Firstly, MCL selected a route with minimum contention among many possible route between source and destination in the route selection procedure; secondly, intermediate nodes did not reply to RREQs in the route discovery procedure. These characteristics reduced contention time in medium reservation procedure and distributed traffic throughout the network. The authors compared the proposed MCL and the Ad-hoc On-demand Distance Vector (AODV) routing protocol. Simulation results showed that MCL outperforms AODV in terms of packet delivery ratio, average end-to-end delay, and normalized routing overhead. In situation where several mobile nodes sent data to a fixed node such as an access point or a server, the proposed routing protocol MCL delivered a high performance gain as a result of load balancing.

- On channel-adaptive routing in an IEEE 802.11b based ad hoc wireless network [49] Lin et al. proposed a reactive ad hoc routing algorithm, called RICA (receiver-initiated channel-adaptive) protocol, to intelligently utilize the multi-rate services (based on different modulation schemes) provided by the IEEE 802.11b standard. The NS-2 simulation results showed that the RICA protocol was highly effective.

- Termite: ad-hoc networking with stigmergy [50] Roth and Wicker presented a biologically inspired algorithm to route messages in mobile wireless ad-hoc networks. The principles of swarm intelligence were used to define a probabilistic algorithm for which routing through paths of maximum throughput was an emergent property. This adaptive algorithm, dubbed Termite, used stigmergy to reduce the amount of control traffic needed to maintain a high data goodput. Stigmergy was a process by which information was indirectly communicated between individuals through their environment. The Termite environment was the contents of all routing tables. The movement of packets was influenced at each node, and communicating nodes observed this influence to update their own tables. Strong routing robustness was achieved through the use of multiple paths; each packet was routed randomly and independently.

- Multihop performance of geographic random forwarding for ad hoc and sensor networks [51] Zorzi and Rao studied a novel forwarding technique based on geographical location of the nodes involved and random selection of the relaying node via contention among receivers. The authors focused on the multihop performance of such a solution, in terms of average
number of hops to reach a destination as a function of the distance and of the average number of available neighbors. An idealized scheme (in which the best relay node was always chosen) was discussed, and its performance was evaluated by means of both simulation and analytical techniques. A practical scheme to select one of the best relays was shown to achieve performance very close to that of the ideal case.

- **Distance-matrix routing: a scalable ad-hoc wireless IP routing** [52]
  Hui and Wu presented a scalable distance-matrix routing algorithm for clusters of nodes. These clusters were defined by GPS coordinates similar to hierarchical routing and geography based routing. The authors showed that the computation and storage requirement of this distance-matrix routing algorithm was scalable and was substantially reduced for large number of mobile nodes. Optimality of routing was maintained. The effect of geographic proximity was shown to reduce computation, message exchange, and route storage requirements. Also, the reduced number of iterations required also improved on the stability of Bellman-Ford type distributed routing algorithms.

- **Performance comparison of routing protocols for ad hoc networks** [53]
  Bertocchi *et al.* made a comparison of Link State, AODV and DSR protocols for two different traffic classes, in a selected environment. The classic Dijkstra was also reported as comparison term. As performance metric, packet delivery fraction, throughput, average delay and energy were considered. The authors showed that AODV and DSR performed well when the network load was moderate, while, if the traffic load was heavy, simple Link State outperformed the reactive protocols and became a good candidate to be used.

- **Shortest path routing in partially connected ad hoc networks** [54]
  Tan *et al.* addressed the issue of data routing in partially connected ad hoc networks. In this situation, data propagation was achieved via mainly pair-wise communication between any two nodes when they were in vicinity. The authors proposed a novel routing framework named Shortest Expected Path Routing (SEPR). Instead of blindly flooding messages in the network, SEPR built up a stochastic model of the ad hoc network and maintained it in a distributed way. A new routing metric, called Expected Path Length, was proposed. By guiding messages flow to shortest expected path nodes, the approach dramatically reduced the number of unnecessary message copies as well as increased the message delivering rate.

- **A simple routing scheme for improving ad hoc network survivability** [55]
  Domingo *et al.* presented a new version of the Dynamic Source Routing (DSR) protocol that favoured the selection of a route containing nodes with high battery levels, in order to maximize the lifetime of the ad hoc mobile network as a whole. This proposal implied little modifications to the original algorithm. After a quantitative analysis, simulation results
indicated that the proposed scheme, SEADSR (Simple Energy Aware DSR), outperformed the standard DSR in terms of network survivability and network capacity.

- **TRANSFER**: Transactions Routing for Ad-hoc Networks with eFFicient EneRgy [56]
  Helmy presented a novel architecture for transaction routing in large-scale ad hoc networks. The author aimed at reducing the total energy consumption of successful delivery as opposed to finding shortest path routes. The architecture used a hybrid approach, where each mobile node obtained information about nodes in its proximity, up to $R$ hops away, using a proactive link state protocol. Beyond the proximity, the author introduced the novel notion of contacts that acted as short cuts to reduce the degrees of separation between the request source and the target. The author proposed an efficient, on-demand, contact selection protocol. No location information was assumed. Extensive simulations were used to evaluate the performance of the protocol in terms of energy consumption and request success rate. The results showed substantial power savings for our contact-based technique, especially for large networks.

- **Efficient on-demand routing for mobile ad-hoc wireless access networks [57]**
  Song et al. considered a mobile ad-hoc wireless access network in which mobile nodes could access the Internet via a stationary gateway node or access point. Mobile nodes that were outside the transmission range of the gateway could continue to communicate with the gateway via a multi-hop connection with their neighboring nodes. The Ad-hoc On-demand Distance Vector (AODV) routing protocol was extended by incorporating the concept of load-balancing (LB). This was called the LB-AODV routing protocol. Simulation results showed that in a congested network environment, the proposed LB-AODV had a higher packet delivery fraction, a lower end-to-end delay and control overhead when compared with both AODV and gossip-based routing protocols.

- **Protocol for dynamic ad-hoc networks using distributed spanning trees [58]**
  Radhakrishnan et al. proposed a distributed algorithm that adapted to the topology by utilizing spanning trees in the regions where the topology was stable, and resorting to an intelligent flooding-like approach in highly dynamic regions of the network. Routing was performed using the spanning trees based on a hold-and-forward or shuttling mechanisms. The authors introduced the notion of connectivity-through-time and the parameter holding-time as new fundamental concepts that could be used by ad-hoc routing algorithms. For various network connectivity scenarios the authors evaluated the impact of these concepts on the performance of ad-hoc routing algorithms.

- **A query scope agent for flood search routing protocols [59]**
  Sucec and Marsic presented a query scope agent (QSA) that assisted in the selection of an appropriate expanding ring search (ERS). The QSA accepted as input, from the user
or network application, a maximum allowable value for route discovery delay. The QSA then estimated network parameter values to determine an ERS approach that satisfied the delay requirement while reducing expected packet transmission overhead. Simulation results showed that it successfully achieved this objective. Further, the QSA incurred little communication and computation overhead, and operated in a distributed and asynchronous fashion.

- Trajectory based forwarding and its applications [60]
  Niculescu and Nath presented trajectory based forwarding (TBF), a novel method to forward packets in a dense ad hoc network that made it possible to route a packet along a predefined curve. It was a hybrid between source based routing and Cartesian forwarding in that the trajectory was set by the source, but the forwarding decision was based on the relationship to the trajectory rather than names of intermediate nodes. The fundamental aspects of TBF were: it decoupled path naming from the actual path; it provided cheap path diversity; it traded off communication for computation. These aspects addressed the double scalability issue with respect to mobility rate and network size. In addition, TBF provided a common framework for many services such as: broadcasting, discovery, unicast, multicast and multipath routing in ad hoc networks. TBF required that nodes knew their position relative to a coordinate system. While a global coordinate system afforded by a system such as GPS would be ideal, approximate positioning methods provided by other algorithms were also usable.

- Ad hoc-VCG: a truthful and cost-efficient routing protocol for mobile ad hoc networks with selfish agents [61]
  Anderegg and Eidenbenz introduced a game-theoretic setting for routing in a mobile ad hoc network that consisted of greedy, selfish agents who accepted payments for forwarding data for other agents if the payments covered their individual costs incurred by forwarding data. In this setting, the authors proposed Ad hoc-VCG, a reactive routing protocol that achieved the design objectives of truthfulness (i.e., it was in the agents’ best interest to reveal their true costs for forwarding data) and cost-efficiency (i.e., it guaranteed that routing was done along the most cost-efficient path) in a game-theoretic sense by paying to the intermediate nodes a premium over their actual costs for forwarding data packets. The authors showed that the total overpayment (i.e., the sum of all premiums paid) was relatively small by giving a theoretical upper bound and by providing experimental evidence. The routing protocol implemented a variation of the well-known mechanism by Vickrey, Clarke, and Groves in a mobile network setting. Finally, the authors analyzed a very natural routing protocol that was an adaptation of the Packet Purse Model with auctions in our setting and show that, unfortunately, it did not achieve cost-efficiency or truthfulness.
• Reactive routing overhead in networks with unreliable nodes [62]
Zhou et al. presented a new mathematical and simulative framework for quantifying the overhead of a broad class of reactive routing protocols, such as DSR and AODV, in wireless variable topology (ad-hoc) networks. The authors focused on situations where the nodes were stationary but unreliable, as was common in the case of sensor networks. The authors explicitly modeled the application-level traffic in terms of the statistical description of the number of hops between a source and a destination. The sensor network was modeled by an unreliable regular Manhattan (i.e. degree four) grid, and expressions for various components of the routing overhead were derived. Results were compared against ns-2 simulations for regular and random topologies, which corroborated the essential characteristics of the analytical results. One of the key insights that could be drawn from the mathematical results was that it is possible to design infinitely scalable reactive routing protocols for variable topology networks by judicious engineering of the traffic patterns to satisfy the conditions presented in this paper.

• PARO: supporting dynamic power controlled routing in wireless ad hoc networks [63]
Gomez et al. introduced PARO, a dynamic power controlled routing scheme that helped to minimize the transmission power needed to forward packets between wireless devices in ad hoc networks. Using PARO, one or more intermediate nodes called ”redirectors” elected to forward packets on behalf of source-destination pairs thus reducing the aggregate transmission power consumed by wireless devices. PARO was applicable to a number of networking environments including wireless sensor networks, home networks and mobile ad hoc networks. The authors presented the detailed design of PARO and evaluated the protocol using simulation and experimentation. The authors showed through simulation that PARO was capable of outperforming traditional broadcast-based routing protocols (e.g., MANET routing protocols) due to its energy conserving point-to-point on-demand design. The authors discussed our experiences from an implementation of the protocol in an experimental wireless testbed using off-the-shelf radio technology. The authors also evaluated the impact of dynamic power controlled routing on traditional network performance metrics such as end-to-end delay and throughput.

• An entropy-based model for supporting and evaluating route stability in mobile ad hoc wireless networks [64]
An and Papavassiliou proposed an entropy-based modeling framework for supporting route stability in mobile ad hoc wireless networks. The basic motivations of the proposed modeling approach stemmed from the commonality observed in the location uncertainty in mobile ad hoc wireless networks and the concept of entropy. The corresponding results demonstrated that the proposed approach and parameters provided an accurate and efficient method of estimating and evaluating the route stability in dynamic mobile
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networks.

• A performance evaluation of a pre-emptive on-demand distance vector routing protocol for mobile ad hoc networks [65]

Mobile ad hoc networks are useful for providing communication support where no fixed infrastructure exists or the deployment of a fixed infrastructure is not economically profitable and movement of communicating parties is allowed. Therefore, it is not possible to establish a priori and fixed paths for message delivery through the network. Because of their importance, routing and packets dropped problems, mainly due to the path breaking, are among the most studied problem in mobile and wireless ad hoc networks. Multi-path protocols can be useful for the purpose of balancing congestion and decreasing the delay, by routing packets along different paths. However, they may allow only source-based load balancing decisions. Boukerche and Zhang presented a pre-emptive ad hoc on-demand distance vector routing protocol for mobile and wireless ad hoc networks. The authors presented the algorithm, discussed its implementation and reported on the performance results of simulation of several workload models on ns-2. The results indicated that a scheme based on scheduling a path-discovery routine before the current in-use link breaks was feasible and that such a mechanism could increase the number of packets delivered and decrease the average delay per packet. It also improved the throughput (packet delivered ratio) and balanced the traffic between different source-destination pairs.

• A stability aware cluster routing protocol for mobile ad hoc networks [66]

An ad hoc network is formed by a collection of mobile nodes without any centralized access point or existing infrastructure. Communications between mobile nodes require routing over multiple-hop wireless paths. Since mobile nodes could be of high mobility, an effective and adaptive routing protocol must have ongoing details of the topology information. However, it wastes limited bandwidth to keep routing information up-to-date and reliable. Thus, one of the crucial design objectives to achieve routing responsiveness and updating efficiency is the minimization of reaction to mobility. Specifically, a scalable and QoS-guaranteed routing protocol is desired for novel multimedia applications in mobile ad hoc networks. Chiu et al. proposed an efficiently repairable routing protocol, called Gravitational Cluster Routing (GCR) Protocol. It contained a stable cluster structure to cover dense areas and avoid articulation nodes. The reaction to mobility could be reduced significantly by unicast. Active routing paths could be maintained locally in each cluster. Besides, repairable levels of active routing paths, which ranked their stabilities, were evaluated. By their aid, the proposed GCR could find routing paths that satisfy different parameters of QoS. These mechanisms could improve the stability of active connections.

• Robust position-based routing in wireless ad hoc networks with irregular transmission
Several papers considered the problem of routing in ad hoc wireless networks using the positions of the mobile hosts. Perimeter routing gives an algorithm that guarantees delivery of messages in such networks without the use of flooding of control packets. However, this protocol is likely to fail if the transmission ranges of the mobile hosts vary because of natural or man-made obstacles. It may fail because either some connections are not considered, which effectively results in a disconnection of the network, or because some crossing connections are used, which could misdirect the message. Barriere et al. described a robust routing protocol, a variant of perimeter routing, which tolerated up to 40% of variation in the transmission ranges of the mobile hosts. More precisely, the protocol guaranteed message delivery in a connected ad hoc wireless network without the use of message flooding whenever the ratio of the maximum transmission range to the minimum transmission range was at most $\sqrt{2}$.

Hierarchical routing in ad hoc mobile networks [68]

Clustering is a method by which nodes are hierarchically organized on the basis of their relative proximity to one another. Routes can be recorded hierarchically, across clusters, to increase routing flexibility. Hierarchical routing greatly increases the scalability of routing in ad hoc networks by increasing the robustness of routes. Belding-Royer presented the Adaptive Routing using Clusters (ARC) protocol, a protocol that created a cluster hierarchy composed of cluster leaders and gateway nodes to interconnect clusters. ARC introduced a new algorithm for cluster leader revocation that eliminated the ripple effect caused by leadership changes. Further, ARC utilized a limited broadcast algorithm for reducing the impact of network floods. The performance of ARC was evaluated by comparing it both with other clustering schemes and with an on-demand ad hoc routing protocol. It was shown that the cluster topology created by ARC was more stable than that created by other clustering algorithms and that the use of ARC could result in throughput increases of over 100%.
Chapter 3

Multicast, Broadcast and Geocast

- Family ACK tree (FAT): supporting reliable multicast in mobile ad hoc networks [69]
  Liao and Jiang proposed a new protocol, called family ACK tree (FAT), to support a reliable multicast service for mobile ad hoc networks. FAT employed a tree-based recovery mechanism that localized ACKs and retransmissions to avoid feedback implosion. To cope with node movements, FAT constructed an ACK tree on which each node maintained reachability information to three generations of nodes on the ACK tree. When a tree was fragmented due to a departed node, the fragments were glued back to the tree using the underlying multicast routing protocol. FAT then adopted an adaptive scheme to recover missed packets that had been multicast to the group during fragmentation and were not repaired by the new reliability agent. Simulation results showed that FAT achieved better performance than existing solutions for the provision of reliable service in ad hoc networks, in terms of reliability, scalability, and delivery efficiency.

- A multicast protocol for physically hierarchical ad hoc networks [70]
  Ko et al. considered mobile ad hoc networks that had physically hierarchical architecture where different types of mobile hosts formed an ad hoc network hierarchy. The authors presented a novel and simple multicasting framework called PHAM (Physical Hierarchy-driven Ad hoc Multicast) for ad hoc networks with various types of mobile hosts having different role, capacity, and mobility pattern. PHAM built a multicast structure at each level of the hierarchy for efficient and scalable multicast message delivery.

- A multicast protocol in ad hoc networks inter-vehicle geocast [71]
  Bachir and Benslimane proposed a new protocol called IVG Inter-Vehicles Geocast which consisted in informing all the vehicles of a highway about any range such as an accident or any other obstacle. In this case, risk areas were determined according to the driving direction and the positioning of the vehicles. These vehicles defined a restricted broadcast group, so-called, multicast group. Multicast group, contrary to the classical methods,
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which used node identifies, was defined temporally and dynamically by the location, speed and driving direction of vehicles. Some simulations and studies of the complexity were given. The results showed that IVG was an efficient broadcast method for secure highway transportation and reduced the number of useful messages.

- Prioritized overlay multicast in mobile ad hoc environments [72]
  Xiao et al. proposed a model to improve the efficiency and robustness of overlay multicast in MANETs by building multiple role-based prioritized trees, possibly with the help of location information about member nodes.

- A reachability-guaranteed approach for reducing broadcast storms in mobile ad hoc networks [73]
  Yang and Chen proposed a reachability-guaranteed approach for reducing broadcast storms in MANET. The approach was based on location awareness, which meant each node in the network needed to equip the positioning device like GPS and exchanged location information in the HELLO message with its neighbors. Three mechanisms were included in the proposed approach: Relay set (RS), neighbor coverage (NC), and transmission order (TO). Simulation results showed that the proposed approach RS+NC+TO had a better performance than the threshold-based schemes and angle-based scheme in terms of 100% reachability, more saved rebroadcast, and shorter average latency to accomplish the broadcast process over the whole network.

- Weight-based clustering multicast routing protocol for mobile ad hoc networks [74]
  Huang et al. proposed a new multicast routing protocol, named weight-based clustering multicast protocol (WCMP), for mobile ad hoc networks. The goal of this work was to improve multicasting performance in ad hoc networks by efficient use of the available knowledge of the networks.

- Obstacle-free geocasting protocol for ad hoc wireless networks [75]
  Chang et al. proposed geocasting protocol for sending short message from a source host to a geocasting region in ad hoc networks. The proposed protocol kept messages away from unpredictable obstacles and created a small flooding region. Experimental results showed that a source host could send a short message to all hosts located in geographical area with a high success rate and low flooding overhead.

- Efficient overlay multicast for mobile ad hoc networks [76]
  Gui and Mohapatra proposed an efficient overlay multicast protocol in MANET environment. A virtual topology gradually adapted to the changes in underlying network topology in a fully distributed manner. A novel source-based Steiner tree algorithm was proposed for constructing the multicast tree. The multicast tree was progressively ad-
justed according to the latest local topology information. Simulations were conducted to evaluate the tree quality.

- **OGHAM**: On-demand global hosts for ad-hoc multicast using minimum distance facility location [77]

  Hu *et al.* proposed a multicast protocol for Ad-hoc networks, called OGHAM, with shorter relay and less concentration via selecting RPs (rendezvous point) from the hosts with minimum hop distance between them and from other normal hosts to these selected RPs rather than the hosts with maximum neighbor degree.

- **A preferred link based multicast protocol for wireless mobile ad hoc networks** [78]

  Sisodia *et al.* proposed an efficient protocol called Preferred Link Based Multicast protocol (PLBM). PLBM used a preferred link approach for forwarding JoinQuery packets. A subset of neighbors of a node were selected using a preferred link based algorithm. These nodes, termed as preferred nodes, were only eligible for further forwarding of JoinQuery packets. The authors also proposed a quick link break detection mechanism that locally repaired broken links. Simulation results showed that the protocol performed better than other existing multicast protocols in terms of packet delivery ratio and control overhead.

- **Adaptive core selection and migration method for multicast routing in mobile ad hoc networks** [79]

  Gupta and Kumar presented distributed core selection and migration protocols for mobile ad hoc networks with dynamically changing network topology. The proposed core location method was based on the notion of median node of the current multicast tree instead of the median node of the entire network. The rationale was that the mobile ad hoc network graphs were in general sparse and, hence, the multicast tree was a good approximation of the entire network for the current purpose. The adaptive distributed core selection and migration method used the fact that the median of a tree was equivalent to the centroid of that tree. The significance of this observation was due to the fact that the computation of a tree’s centroids did not require any distance information. The authors used the cost of multicast tree as the sum of weights of all the links in the tree, which signified the total bandwidth consumed for multicasting a packet. The simulation results showed that for large size networks, the ratio $\frac{\text{Cost}_\text{TM}}{\text{Cost}_\text{GM}}$ lay between 0.8 to 1.2 for different multicast groups. Further, as the size of the multicast group increased the ratio approached 1.

- **On reducing broadcast redundancy in ad hoc wireless networks** [80]

  Lou and Wu analyzed some deficiencies of the dominant pruning algorithm and proposed two better approximation algorithms: total dominant pruning and partial dominant pruning. Both algorithms utilized 2-hop neighborhood information more effectively to reduce
redundant transmissions. Simulation results of applying these two algorithms showed performance improvements compared with the original dominant pruning. In addition, two termination criteria were discussed and compared through simulation under both the static and dynamic environments.

- Adaptive Approaches to Relieving Broadcast Storms in a Wireless Multihop Mobile Ad Hoc Network [81]
  In a multihop mobile ad hoc network, broadcasting is an elementary operation to support many applications. Previously, it is shown that naively broadcasting by flooding may cause serious redundancy, contention, and collision in the network, which is referred to as the broadcast storm problem. Several threshold-based schemes are shown to perform better than flooding in that work. However, how to choose thresholds also poses a dilemma between reachability and efficiency under different host densities. Tseng et al. proposed several adaptive schemes, which could dynamically adjust thresholds based on local connectivity information. Simulation results showed that these adaptive schemes could offer better reachability as well as efficiency as compared to the previous results.

- The use of multiuser detectors for multicasting in wireless ad hoc CDMA networks [82]
  Sankaran and Ephremide addressed the issue of performance of linear multiuser detectors for a multicasting application in an ad hoc wireless network. Using a code-division multiple-access (CDMA) framework, the authors demonstrated how capacity results for multiuser detectors could be adapted to do session admission control for the multicasting problem. The authors then developed a multicast routing algorithm for ad hoc wireless networks. Using the session admission control mechanism and the multicast routing algorithm, the authors evaluated the performance of three different linear multiuser detectors for the multicasting application.

- A novel mechanism for flooding based route discovery in ad hoc networks [83]
  To avoid the problem of wireless broadcast storm, the Random Rebroadcast Delay (RRD) approach was introduced in the process of flooding-based route discovery in DSR and AODV protocols. Li and Mohapatra identified the "next-hop racing" phenomena due to the RRD approach and proposed a Positional Attribute based Nexthop Determination Approach (PANDA) to address this problem. Based on positional attributes such as the relative distance, estimated link lifetime, transmission power consumption, an intermediate node would identify itself as good or bad candidate for the next-hop node and used different rebroadcast delay accordingly. Through simulations the authors evaluated the performance of PANDA using path optimality, end-to-end delay, and transmission power consumption. Simulation results showed that PANDA could: (a) improve path optimality, and end-to-end delay, (b) help find data paths with only 15% 40% energy consumption
• Broadcast traffic in ad hoc networks with directional antennas [84]
Wang and Garcia-Luna-Aceves explored the use of directional antennas to improve the performance of broadcasting in ad hoc networks. The authors investigated both the performance of unicast traffic in the presence of broadcast traffic and the performance of broadcast traffic when mixed with unicast traffic, which was different from previous investigations reported in the literature in which broadcast traffic was investigated in isolation. Through extensive simulation experiments with three MAC schemes, the authors showed that throughput and delay could vary widely even in networks in which nodes were uniformly distributed. The authors also showed that the use of a MAC protocol that utilized directional antennas could help to improve the performance of broadcast traffic in ad hoc networks, in terms of both throughput and delay, through a more aggressive channel access scheme that maximized spatial reuse.

• A reliable broadcast algorithm with selected acknowledgements in mobile ad hoc networks [85]
Luo and Wu propose a simple broadcast algorithm to provide thigh delivery ratio. Among the 1-hop neighbors of the sender, only selected forward nodes would send acknowledgements to confirm their receipt of the packet. Forward nodes were selected in such a way that all the sender’s 2-hop neighbors were covered. Moreover, no acknowledgement was needed from non-forward 1-hop neighbors, each of which was covered by at least two forward neighbors. The sender waited for the acknowledgements from all of its forward nodes. If not all acknowledgements were received, the sender would resend the packet until the maximum number of retries was reached. Simulation results showed that the algorithm had high delivery ratio and low end-to-end delay for a broadcast operation.

• Robust and cost-efficient group communication using overlay multicast in mobile ad hoc networks [86]
Previous multicast schemes for MANET (Mobile Ad Hoc Networks) are mostly classified as treebased schemes and mesh-based schemes depending on their multicast delivery structure. Tree-based schemes cannot cope with network mobility due to frequent tree reconfiguration. On the other hand, mesh-based schemes waste unnecessary resource due to delivery along multiple paths. Kim et al. proposed to use an overlay multicast to handle network mobility efficiently with minimized resource. In the scheme, DDT (Data Delivery Tree) could remain static as long as unicast route between members that were related to data forwarding remains reachable. Thus, it could not only minimize the effects of network mobility, but also bring about low additional control overhead. Such distinct advantages were specifically evaluated through the results of the simulation.
CHAPTER 3. MULTICAST, BROADCAST AND GEOCAST

- Adaptive core multicast routing protocol [87]
  The Adaptive Core Multicast Routing Protocol (ACMRP) is proposed for multicast routing in ad hoc networks. ACMRP is on demand core-based multicast routing protocol that is based on a multicast mesh. In ACMRP, a core is not well-known and it adapts to the current network topology and group membership. The enhanced adaptivity minimizes the core dependency and, accordingly, improves performance and robustness of ACMRP. A multicast mesh is created and maintained by the periodic flooding of the adaptive core. Since the flooding traffic is evenly maintained and a mesh provides rich connectivity among group members, ACMRP can achieve efficiency, scalability, and effectiveness. Park et al. evaluated scalability and performance of ACMRP via simulation.

- Manycast: exploring the space between anycast and multicast in ad hoc networks [88]
  Carter et al. presented manycast and discussed its use as a communication primitive, with specific attention to ad hoc networks. The authors advocated manycast support at the network layer. A manycast routing protocol enabled an application to contact several nearby network nodes that implemented a distributed service. The authors analyzed some approaches to manycast, including some application layer implementations. This evaluation supported their claim that manycast must be implemented in the network layer for effective operation in ad hoc networks. The authors presented several extensions to ad hoc routing protocols that could provide manycast support with minimal implementation effort. Through analysis and extensive simulation, the authors explored the behavior of these approaches to manycast, finally providing recommendations to implementors.

- Obstacle-free geocasting protocols for single/multi-destination short message services in ad hoc networks [89]
  Chang et al. proposed geocasting protocols for sending short message from a source host to single or multiple geocasting regions in ad hoc networks. The proposed protocols kept messages away from unpredictable obstacles and created a small flooding region. Experimental results showed that a source host could send a short message to all hosts located in single or multiple geographical areas with a high success rate and low flooding overhead.

- Reliable MAC layer multicast in IEEE 802.11 wireless networks [90]
  Multicast/broadcast is an important service primitive in networks. It is supported by all IEEE 802.x standards, including 802.11. The IEEE 802.11 multicast/broadcast protocol is based on the basic access procedure of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). This protocol does not provide any media access control (MAC) layer recovery on multicast/broadcast frames. As a result, the reliability of the multicast/broadcast service is reduced owing to the increased probability of lost frames result-
ing from interference or collisions. Recently, a few MAC protocols have been proposed to enhance the reliability and the efficiency of the 802.11 multicast/broadcast protocol. Sun et al. observed that these protocols were still unreliable or inefficient. To redress the problems of reliability and efficiency, the authors proposed a reliable Batch Mode Multicast MAC protocol (BMMM), which in most cases reduced the number of contention phases from $n$ to 1, where $n$ was the number of intended receivers in the multicast/broadcast. This considerably reduced the time required for a multicast/broadcast. The authors then proposed a Location Aware Multicast MAC protocol (LAMM), which used station location information to further improve upon BMMM. Extensive analysis and simulation results validated the reliability and efficiency of our multicast MAC protocols.

- **Forward-node-set-based broadcast in clustered mobile ad hoc networks [91]**  
  A taxonomy of broadcast protocols in mobile ad hoc networks (MANETs) is given where protocols are classified into four groups: global, quasi-global, quasi-local, and local. The taxonomy also divides protocols based on the nature of algorithms: probabilistic and deterministic. The locality of maintenance also plays an important role in evaluating the protocol. An important objective in designing a broadcast protocol is to reduce broadcast redundancy to save scarce resources such as energy and bandwidth and to avoid the broadcast storm problem. This objective should be achieved without introducing excessive overhead and time delay, measured by sequential rounds of information exchanges. This is done by choosing a small forward node set that forms a connected dominating set (CDS) to carry out a broadcast process. Wu and Lou proposed a clustered network model in which each node was a clusterhead in the clustered architecture. Clusterheads were connected by carefully selecting non-clusterhead nodes locally at each clusterhead to connect clusterheads within the 2.5-hop coverage, a novel notion proposed in this paper. Information of neighbor clusterheads was piggybacked on the broadcast packet to further reduce each forward node set. It was shown that this approach was quasi-local with locality of maintenance. In addition, this approach had a constant approximation ratio to the minimum connected dominating set (MCDS) and generated a small forward node set in the average case. Comparisons were also done through simulation with representative protocols from each of the four groups of protocols based on the proposed taxonomy. The authors also simulated the proposed broadcast protocol in a dynamic network and analyzed its performance.

- **MHMR: mobility-based hybrid multicast routing protocol in mobile ad hoc wireless networks [92]**  
  The field of mobile ad hoc networking has enjoyed dramatic increase in popularity over the last few years. However, owing to the fact that such networks have dynamic, sometimes rapidly changing, random, multihop topologies, the development of efficient and appli-
ble multicast routing protocols presents many issues and challenges. An and Papavassiliou proposed a Mobility-based Hybrid Multicast Routing (MHMR) protocol suitable for mobile ad hoc networks. The main features that the proposed protocol introduced were the following: (i) mobility-based clustering and group-based hierarchical structure, in order to effectively support stability and scalability; (ii) group-based (limited) mesh structure and forwarding tree concepts, in order to support the robustness of the mesh topologies, which provided limited redundancy and the efficiency of tree forwarding simultaneously; and (iii) combination of proactive and reactive concepts that provided low route acquisition delay and low overhead. The use of dynamic mobility-based clustering as the underlying structure was motivated by the observation that in mobile ad hoc networks communications were often among teams that tended to coordinate their movements, and as a result the authors could dynamically and adaptively partition the network into several groups, each with its own mobility characteristics and behaviors. In the protocol the authors supported the creation of a limited mesh structure based on the clusterheads of the various created clusters, and not among all the members that participated in the multicast session and route, thereby reducing significantly the complexity of the created mesh topology. The performance evaluation of the proposed protocol was achieved via modeling and simulation. The corresponding results demonstrated the proposed multicast protocol’s efficiency in terms of packet delivery ratio, scalability, control overhead, end-to-end delay as a function of mobility, packet transmission rate, and multicast group size.
Chapter 4

Flooding

• Probabilistic broadcast for flooding in wireless mobile ad hoc networks [93]
  Sasson et al. explored the phase transition phenomenon observed in percolation theory and random graphs as a basis for defining probabilistic flooding algorithm. By considering ideal and realistic models, the authors acquired a better understanding of the factors that determined phase transition, the consequences of the passage to realistic MANET conditions and to what extent we might benefit from probabilistic flooding in real MANET networks.

• Efficient flooding in ad hoc networks: a comparative performance study [94]
  Efficient flooding schemes to choose a dominant set of nodes have been recently proposed in a hoc networks. Yi et al. compared the performance of a set of representative schemes via simulation using as criteria the flooding efficiency and the delivery ratio.

• Efficient flooding with passive clustering-an overhead-free selective forward mechanism for ad hoc/sensor networks [95]
  Scalability and density are the major limitations when ad hoc routing schemes are applied to sensor networks. Kwon presented a novel efficient flooding method with Passive clustering (PC) suitable for on-demand routing protocols. PC classified ad hoc/ensor nodes into critical and noncritical nodes without any extra transmission. By 2-b piggybacking and monitoring user traffic (e.g., data polling requests from a sink), PC deployed the clustering structure "for free". Moreover, PC made even the first flooding as efficient as all subsequent floodings (i.e., no initialization overhead). As a result, PC reduced control overhead of ad hoc routing protocols significantly and, as a consequence, enabled ad hoc routing in large, dense sensor networks. The resulting structure could be utilized in cluster-based ad hoc network/sensor networking as well as for active node selection.
Chapter 5

Transport

- Performance improvement of TCP on a wireless ad hoc network [96]
  Sugano and Murata described a new technique for improving TCP performance in an ad hoc network that used a table-driven type of routing protocol paying attention to short-duration link failure. The authors took as the object of research a Flexible Radio Network (FRN) which was an ad hoc network for data collection. The authors also evaluated the case in which the effect of the collision of a data packet and an ACK packet was suppressed by Delayed ACK and resending the ACK packet preferentially. Simulation showed that the combination of these improvements could increase TCP throughput about 20%.

- TCP performance over multipath routing in mobile ad hoc networks [97]
  Lim et al. investigated TCP performance over a multipath routing protocol. The authors found that most times, using multiple paths simultaneously might actually degrade TCP performance. This was partly due to frequent out-of-order packet delivery via different paths. However, under another multipath routing scheme called backup path routing, TCP was able to gain improvements against mobility. Simulation results showed that by careful selection of the multipath routing strategies, TCP performance could be improved by more than 30% even under very high mobility.

- An enhancement scheme for TCP over mobile ad hoc networks [98]
  In a Mobile Ad Hoc Network, temporary link failures and route changes occur frequently. With the assumption that all packet losses are due to congestion, TCP performs poorly in such an environment. Choi et al. proposed a new mechanism called TSR, TCP-aware Source routing, which could improve TCP performance in wireless ad hoc networks. TSR added a hold state to an existing routing protocol to reduce consecutive timeouts, retransmissions, and out-of-ordered packets in TCP. In the simulation study, TSR achieved up to a 60% improvement in performance, without requiring any TCP stacks in end systems to be modified.
• A transport protocol for supporting multimedia streaming in mobile ad hoc networks [99] Fu et al. described the design and implementation of a transmission control protocol (TCP)-friendly transport protocol for ad hoc networks. The key design novelty was to perform multimetric joint identification for packet and connection behaviors based on end-to-end measurements. The NS-2 simulations showed significant performance improvement over wired TCP friendly congestion control and TCP with explicit-link-failure-notification support in ad hoc networks.

• On setting TCP’s congestion window limit in mobile ad hoc networks [100] Improving TCP performance has long been the focus of many research efforts in mobile ad hoc networks (MANET). Chen et al. addressed one aspect of this endeavor: how to properly set TCP’s congestion window limit (CWL) to achieve optimal performance. The authors turned the problem of setting TCP’s optimal CWL into identifying the bandwidth-delay product (BDP) of a path in MANET. The authors first showed and proved that, independent of the MAC layer protocol being used, the BDP of a path in MANET could not exceed the round-trip hop-count (RTHC) of the path. The authors further refined this upper bound based on the IEEE 802.11 MAC layer protocol, and showed that in a chain topology, a tighter upper bound exists which was approximately 1/5 of the RTHC of the path. Based on this tighter bound, the authors proposed an adaptive CWL setting strategy to dynamically adjust TCP’s CWL according to the current RTHC of its path. Using ns-2 simulations, the authors showed that this simple strategy improved TCP performance by 8% to 16% in a dynamic MANET environment.

• SCTP with an improved cookie mechanism for mobile ad-hoc networks [101] The Stream Control Transport Protocol (SCTP) is a new transport layer protocol that has been designed to provide reliable transport over IP networks. While the Transport Control Protocol (TCP) is the most popular transport protocol in the IP networks, it falls short with regard to security - more specifically, resilience to Denial-of-Service (DoS) attacks, such as SYN attacks. The need for resilience to DoS attacks is obvious, and SCTP provides for this resilience via its improved handshake mechanism and the Cookie feature. Joe discussed the SCTP simulation with particular emphasis on resilience to DoS attacks. As revealed by the detailed simulation study, the increased DoS resilience came with increased overheads. While DoS resilience was extremely critical, reducing overheads in the resource-constrained wireless environment also assumed paramount importance. Hence the authors proposed an innovative Cookie mechanism with a combination of cache and INIT packet repetition to minimize the communication overhead and simultaneously to maximize security associated with SCTP’s DoS resilience over mobile ad-hoc networks.

• Enhancing TCP fairness in ad hoc wireless networks using neighborhood RED [102]
Significant TCP unfairness in ad hoc wireless networks has been reported during the past several years. This unfairness results from the nature of the shared wireless medium and location dependency. If we view a node and its interfering nodes to form a “neighborhood”, the aggregate of local queues at these nodes represents the distributed queue for this neighborhood. However, this queue is not a FIFO queue. Flows sharing the queue have different, dynamically changing priorities determined by the topology and traffic patterns. Thus, they get different feedback in terms of packet loss rate and packet delay when congestion occurs. In wired networks, the Randomly Early Detection (RED) scheme was found to improve TCP fairness. Xu et al. showed that the RED scheme did not work when running on individual queues in wireless nodes. The authors then proposed a Neighborhood RED (NRED) scheme, which extended the RED concept to the distributed neighborhood queue. Simulation studies confirmed that the NRED scheme could improve TCP unfairness substantially in ad hoc networks. Moreover, the NRED scheme acted at the network level, without MAC protocol modifications. This considerably simplified its deployment.

- Performance evaluation of TCP algorithms in multi-hop wireless packet networks [103]

Wireless packet ad hoc networks are characterized by multi-hop wireless connectivity and limited bandwidth competed among neighboring nodes. Xu and Saadawi investigated and evaluated the performance of several prevalent TCP algorithms in this kind of network over the wireless LAN standard IEEE 802.11 MAC layer. After extensively comparing the existing TCP versions (including Tahoe, Reno, New Reno, Sack and Vegas) in simulations, the authors showed that, in most cases, the Vegas version worked best. The authors revealed the reason why other TCP versions performed worse than Vegas and showed a method to avoid this by tuning a TCP parameter - maximum window size. Furthermore, the authors investigated the performance of these TCP algorithms when they ran with the delayed acknowledgment (DA) option defined in IETF RFC 1122, which allowed the TCP receiver to transmit an ACK for every two incoming packets. The authors showed that the TCP connection can gain 15 to 32 per cent good-put improvement by using the DA option. For all the TCP versions investigated in this work, the simulation results showed that with the maximum window size set at approximately 4, TCP connections perform best and then all these TCP variants differed little in performance.
Chapter 6

Data Cache

- A caching scheme for routing in mobile ad hoc networks and its application to ZRP [104] Beraldi and Baldoni addressed the problem of designing a proactive cache scheme that did not rely on any timer-based mechanism. This scheme guaranteed that valid cached routes were never removed while stale routes were removed aggressively. This proactive cache scheme was embedded in the Zone Routing Protocol (ZRP) framework and evaluated by an extensive simulation study.

- Cache data access system in ad hoc networks [105] Since nodes in mobile wireless ad hoc networks may not always be able to access original data that they want, methods for distributing caches of data have been developed. We propose not only a cache allocation method but also a comprehensive system for accessing cached data, which includes such three steps; distributing caches beforehand, discovering the caches, and accessing the discovered cache. Moriya and Aida especially focused on cache discovery problem and proposed a ”self-resolver” paradigm, in which a client user itself queried and measured which node it should access. In addition to the self-resolver cache discovery framework, the authors considered stability of a multihop route as probability, which could be obtained by two definitions: neighbor-independent link model or neighbor-dependent link model. The route stability models were utilized not only for cache data access system but also for any applications in ad hoc networks. Evaluations of the self-resolver method were carried out with the route stability models. Experimental results showed that, in comparison with query range limitation with hop count, query range limitation with the route stability models could reduce the number of query packets and discover more cache-keeping nodes.

- Cooperative cache-based data access in ad hoc networks [106] A cooperative cache-based data access framework lets mobile nodes cache the data or the path to the data to reduce query delays and improve data accessibility.
• Neighbor caching in multi-hop wireless ad hoc networks [107]

Cho et al. proposed a neighbor caching strategy to overcome the overhead of multi-hop wireless communications. Neighbor caching made a node able to expand its caching storage instantaneously by storing its data in the storage of idle neighbors. The authors also presented the ranking based prediction that selected the most appropriate neighbor which data could be stored in. The ranking based prediction was an adaptive algorithm that adjusted the frequency of neighbor caching and made neighbor caching flexible according to the idleness of nodes.
Chapter 7

Security

- Routing security and data confidentiality for mobile ad hoc networks [108]

The salient nature of ad hoc networks render them vulnerable to numerous types of security attacks. The dynamic feature of ad hoc networks makes enforcement of security becomes an extremely challenging issue. The main problem of many proposed routing protocols for ad hoc networks is that these protocols have critical susceptibilities to security attacks. Effective operation of ad hoc networks depends on the maintenance of correct routing information of the network. Nevertheless, securing routing protocols without securing network transmissions is not enough, as a result, the major focuses are to secure the routing protocol and likewise to protect data transmission. Ng and Seah presented the Secure Routing Protocol (SEROP) which achieved data confidentiality and secures the routing protocol for mobile ad hoc networks without demanding any unrealistic assumptions.

- Context aware detection of selfish nodes in DSR based ad-hoc networks [109]

There can be several sophisticated attacks motivated by selfish, resource saving nature of nodes in a civilian co-operation based ad-hoc network. Distributed rating model based castigation can be useful to discourage selfish nodes from performing these attacks. Even if an attacker is detected, it is hard to charge an accused node in a dynamic environment of an ad-hoc network. Paul and Westhoff detected a large range of attacks on dynamic source routing (DSR) protocol and the originator of the attack. The authors provided a mechanism to inform other nodes of the system about the accused, provided a context aware inference scheme to blame the accused and malicious accuser without doubt. The authors achieved this with minimal extension of DSR and in a cost effective manner.

- Security equipment in ad hoc networks [110]

Due to the inherent quality of wireless mobile networks and the lack of center control units,
the security is always a weak point for ad hoc networks. Othman and Xue proposed a new concept, that is, the security equipment in ad hoc networks. The authors considered that a user could use an infrastructure ad hoc without completely putting his resources to the network. He could become invisible at the routing level without loss his abilities of receiving and sending. Thus he would be protected at the equipment level.

- A multipath ad hoc routing approach to combat wireless link insecurity [111]
  In order to enhance the security on the existing development efforts, Lee et al. proposed a novel multipath routing approach to combat the link insecurity problem at a higher protocol layer. This approach did not require the application to user sophisticated encryption technologies that might be too heavy burdens for mobile devices. Based on the suggested confidentiality measurement model, the authors found that the proposed multipath ad hoc routing technique, called Secure Multipath Source Routing (SMSR) was highly effective.

- An analysis of Bluetooth security vulnerabilities [112]
  Hager and Midkiff described the Bluetooth system with an emphasis on its security features and known vulnerabilities. Additional security vulnerabilities were discovered using a scheme called VERDICT. These vulnerabilities were compared to vulnerabilities found in the IEEE 802.11 wireless local area network standard with VERDICT. Vulnerabilities were found as a result of poor improper validation, exposure, and randomness. These vulnerabilities included device address validation, invalid states, and exposed keys.

- Routing security in wireless ad hoc networks [113]
  Deng et al. studied the routing security issues of MANETs, and analyzed in detail one type of attack-the "black hole" problem-that could easily be employed against the MANETs. The authors also proposed a solution for the black hole problem for ad hoc on-demand distance vector routing protocol.

- Self-organized public-key management for mobile ad hoc networks [114]
  Capkun et al. proposed a fully self-organized public-key management system that allowed users to generate their public-private key pairs, to issue certificates, and to perform authentication regardless of the network partitions and without any centralized services. Furthermore, the approach did not require any trusted authority, not even in the system initialization phase.

- The Resurrecting Duckling: security issues for ubiquitous computing [115]
  Peer-to-peer and ubiquitous computing systems involve many principals, but their network connectivity is intermittent and not guaranteed. Traditional approaches to authentication, from Kerberos to public-key certificates, are therefore unworkable, because they
rely on online connectivity to an authentication or revocation server. Stajano and Anderson discussed the Resurrecting Duckling security policy model. The traditional taxonomy of security threats identified three main classes which were considered: confidentiality, integrity or availability.

- **Bootstrapping security associations for routing in mobile ad-hoc networks [116]**
  To date, most solutions proposed for secure routing in mobile ad-hoc networks (MANETs), assume that secure associations between pairs of nodes can be established on-line; e.g., by a trusted third party, by distributed trust establishment. However, establishing such security associations, with or without trusted third parties, requires reliance on routing layer security. Bobba *et al.* eliminated this apparent cyclic dependency between security services and secure routing in MANETs and showed how to bootstrap security for the routing layer. The authors used the notion of statistically unique and cryptographically verifiable (SUCV) identifiers to implement a secure binding between IP addresses and keys that was independent of any trusted security service. The authors illustrated the solution with the Dynamic Source Routing (DSR) protocol and compared it with other solutions for secure routing.

- **Pre-loaded key based multicast and broadcast authentication in mobile ad-hoc networks [117]**
  The nature of Mobile Ad hoc NETworks (MANET), demands stringent requirements on primitives that could be used to secure such networks. Mobility imposes restrictions on memory and processor requirements due to limited battery life. The ad hoc nature warrants schemes that could operate for extended periods without referring to a Trusted Authority (TA). Additionally, any enabling scheme for security should be able to scale well. Ramkumar and Memon introduced a novel key management scheme, RPS - Random Preloaded Subset key distribution - which satisfied all the above requirements. More specifically, RPS was an $n$-secure $r$-conference key predistribution scheme. The authors investigated the applicability of RPS in securing MANETs.

- **Intrusion detection techniques for mobile wireless networks [118]**
  The rapid proliferation of wireless networks and mobile computing applications has changed the landscape of network security. The traditional way of protecting networks with firewalls and encryption software is no longer sufficient and effective. It is necessary to search for new architecture and mechanisms to protect the wireless networks and mobile computing application. Zhang *et al.* examined the vulnerabilities of wireless networks and argued that intrusion detection must be included in the security architecture for mobile computing environment. The authors developed such an architecture and evaluated a key mechanism in this architecture, anomaly detection for mobile ad-hoc network, through
Simulation experiments.

- Adaptive security for multilevel ad hoc networks [119]

Secure communication is critical in military environments in which the network infrastructure is vulnerable to various attacks and compromises. A conventional centralized solution breaks down when the security servers are destroyed by the enemies. Kong et al. designed and evaluated a security framework for multilevel ad hoc wireless networks with unmanned aerial vehicles (UAVs). In battlefields, the framework adapted to the contingent damages on the network infrastructure. Depending on the availability of the network infrastructure, the design was composed of two modes. In infrastructure mode, security services, specifically the authentication services, were implemented on UAVs that featured low overhead and flexible managements. When the UAVs failed or were destroyed, the system seamlessly switched to infrastructureless mode, a backup mechanism that maintained comparable security services among the surviving units. In the infrastructureless mode, the security services were localized to each node’s vicinity to comply with the ad hoc communication mechanism in the scenario. The authors studied the instantiation of these two modes and the transitions between them. The implementation and simulation measurements confirmed the effectiveness of the design.
Chapter 8

Medium Access Control

- A MAC protocol supporting multiple traffic over mobile Ad Hoc networks [120] Tian et al. presented a multi-channel MAC protocol that supports multiple traffics. The dynamic channel selection scheme by receiver decision was implemented and the number of the data channel was independent of the network topology. An adaptive back off algorithm was employed to provide service differentiation for delay sensitive and best-effort traffic. The simulation results showed that it could support multiple traffics and provided a certain QoS guarantee.

- CoS guarantee control for wireless LAN [121] Ogawa et al. investigated CoS (class of service) in an ad hoc network. The authors proposed a novel media access control using weight for CoS in an ad hoc network. The scheme consisted of carrier sense, packet scheduling for access timing related to CoS amid collision avoidance. The simulation results showed that the scheme was of high performance compared with conventional methods, and was able to perform CoS control.

- Throughput and fairness in a hybrid channel access scheme for ad hoc networks [122] Wang and Garcia-Luna-Aceves proposed a novel hybrid channel access scheme that combines sender-initiated collision-avoidance handshakes for multi-hop ad hoc networks. The new scheme was compatible with the popular IEEE 802.11 MAC protocol and involved adding very simple queue management and bookkeeping work mechanisms. Simulation experiments showed that the new scheme could alleviate the fairness problems existing in applications running on either UDP or TCP with almost no degradation in throughput. More importantly, it was also shown that without explicit information exchange among nodes, the fairness problem could not be solved conclusively.

- Fair threshold energy level of energy efficient MAC scheme for energy-limited ad hoc networks [123]
Jin and Cho previously proposed an energy efficient medium access control (MAC) algorithm based on reservation and scheduling for ad hoc wireless networks. Here, the fair threshold energy level was derived by mathematical analysis for pseudo base station reselection in the energy efficient MAC protocol.

- **A simple distributed PRMA for MANETs [124]**
  Jiang *et al.* extended the classical centralized and slotted packet reservation multiple access (PRMA) scheme to a simple distributed PRMA (D-PRMA) as a MAC scheme for MANETs, with emphasis on voice application support. The major efforts of D-PRMA included 1) a simple slot reservation mechanism for voice traffic at the level of "talkspurt" without relying on any central entity and 2) a simple solution for the hidden and exposed terminal problems uniquely present in wireless ad hoc environments. The performance of D-PRMA was investigated by analysis and computer simulations in comparison with IEEE 802.11. The results showed that D-PRMA is much more suitable than IEEE 802.11 for voice application.

- **ROAD: a variable-radius MAC protocol for ad hoc wireless networks [125]**
  Yeh proposed the Request-to-send/Object-to-send/Agree-to-send/Declare-to-receive (ROAD) medium access control (MAC) protocol for heterogeneous ad-hoc networking. ROAD could support both fixed-radius and variable-radius transmissions, either single-channel, dual control/data channel, or multichannel ad hoc networks, both unicast and reliable multicast, as well as prioritization and QoS guarantees. ROAD also enabled several novel ad-hoc networking paradigms and switching techniques. Moreover, the techniques and mechanisms proposed for ROAD could be applied to obtain extensions to IEEE 802.11 and Bluetooth with better performance or stronger capability for coexistence.

- **An improved data flushing MAC protocol for IEEE 802.11 wireless ad hoc network [126]**
  Sheu *et al.* proposed a data flushing data transfer (DFDT) protocol. DFDT was capable of sending out multiple data packets from the upper layer, after acquiring channel access by a successful contention, within one frame which we call compiled MPDU (cMPDU). Right after the transmission of the data frame, the destination nodes would reply an positive/negative acknowledgement in a consecutive manner. By using this method, the protocol overhead was relatively lowered while retaining service quality and the waste of bandwidth for contention was also reduced. Simulation results showed that DFDT could handle higher traffic load and had better throughput than the IEEE 802.11 MAC protocol.

- **Multi-code MAC for multi-hop wireless ad hoc networks [127]**
  Jin and Cho proposed the multi-code MAC scheme considering multimedia packets in
multi-hop wireless ad hoc networks with flat architecture. The multi-code MAC enhanced the previous multichannel MACs, which simultaneously allocated multiple codes to the sender after the exchange of RTS/CTS/ACK messages through common code. The authors performed a simulation to evaluate our multi-code MAC in view of throughput and average access delay.

- Performance, optimization, and cross-layer design of media access protocols for wireless ad hoc networks [128]
  Toumpis and Goldsmith introduced a methodology for studying wireless ad hoc networks in a multihop traffic environment. The approach was to use theoretical upper bounds on network performance for evaluating the effects of various design choices: the authors focused on power control, the queuing discipline, the choice of routing and media access protocols, and their interactions. Using this framework, the authors then concentrated on the problem of medium access for wireless multihop networks. The authors first study CSMA/CA, and find that its performance strongly depended on the choice of the accompanying routing protocol. The authors then introduced two protocols that outperformed CSMA/CA, both in terms of energy efficiency and achievable throughput. The Progressive Back Off Algorithm (PBOA) performs medium access jointly with power control. The Progressive Ramp Up Algorithm (PRUA) sacrificed energy efficiency in favor of higher throughput. Both protocols slotted time, and were integrated with queuing disciplines that were more relaxed than the First In First Out (FIFO) rule. They were totally distributed and the overhead they require did not increase with the size and node density of the network.

- A load awareness medium access control protocol for wireless ad hoc network [129]
  Chao et al. proposed a new load awareness wireless ad hoc MAC protocol (which was called the LA protocol) that exploited the benefits of both contention-based and contention-free protocols. A contention-based MAC protocol was used when system was light-loaded and a contention-free one was used otherwise. The LA protocol, which operated distributed and was fully compatible with IEEE 802.11 wireless local area network (WLAN) standard, could switch smoothly between the contention-based protocol and the contention-free one. Simulation results showed that the protocol indeed extracted the better part of two kinds of protocols and performs well in all system loads.

- NICE - a decentralized medium access control using neighborhood information classification and estimation for multimedia applications in ad hoc 802.11 wireless [130]
  The desired properties of a medium access control (MAC) protocol in mobile ad hoc network (MANET) include (1) meet quality of service (QoS) requirements for real-time nodes, (2) be decentralized, (3) achieve fairness from viewpoint of throughput or energy
consumption, and (4) be immune to the hidden node problem. Chen et al. proposed a new MAC scheme satisfying all of above four properties. The protocol could support real-time traffic and satisfy QoS requirements, and could achieve fairness among non-real-time nodes. Also, without using any centralized control, it could be easily deployed in MANET. An analytic model of the protocol’s throughput was also developed. The authors compared the protocol’s throughput obtained from its analytic model and simulation to validate each other.

- **ADHOC**: a new, flexible and reliable MAC architecture for ad-hoc networks [131]

  Borgonovo et al. presented a MAC architecture able to solve the above issues in environments with no power consumption limitation, such as networks for inter-vehicle communications. This new architecture was based on a completely distributed access technique, RR-ALOHA, capable to dynamically establish on a slotted/framed structure a reliable single-hop broadcast channel for each active terminal on the network. Though the proposed MAC uses a slotted channel, it could be adapted to operate on the physical layer of different standards, including the UMTS terrestrial radio access TDD, and the IEEE 802.11. The authors presented the mechanisms that composed the new MAC: the basic RR-ALOHA protocol, an efficient broadcast service and the reservation of point-to-point channels that exploited parallel transmissions.

- **Performance evaluation of multiple access protocols for ad hoc networks using directional antennas** [132]

  ElBatt introduced a novel reservation based multiple access protocol for ad hoc networks using directional antennas. First, the authors investigated the limitations of the extreme reservation schemes, namely omni-directional and directional reservations. The authors highlighted the trade-off between spatial reuse (favors directional reservation) and control/data packet collisions (favors omni-directional reservation). Next, the authors showed that the so-called hybrid reservation schemes fail to balance the trade-off as well. Therefore, the authors introduced a novel algorithm that balances the aforementioned trade-off via sending reservation messages that carried information about the required direction of transmission, in all unblocked directions. In addition, the authors introduced candidate techniques for handling new types of collisions inherent to directional antennas. Finally, the authors conducted a simulation study that showed considerable performance gains of the proposed scheme over the omni-directional, directional, and hybrid reservation paradigms.

- **Colorwave**: a MAC for RFID reader networks [133]

  Waldrop presented Colorwave, a medium access control (MAC) protocol designed for wireless sensor networks such as radio frequency identification (RFID) reader networks.
A network of readers would collaborate for a common application such as item-level monitoring in supply chain management. Readers might be deployed in an ad hoc manner, and readers must not interfere with one another’s reader-to-tag communication. Colorwave capitalized on the localized nature of reader-to-tag communications to provide an on-line, distributed, and localized MAC protocol that minimized reader-to-reader interference.

- **Interleaved carrier sense multiple access:** an efficient MAC protocol for ad hoc wireless networks [134]

  Wireless networks are inherently limited by the bandwidth constraint. MAC protocols for Wireless Local Area Networks (WLANs) play the important role of arbitrating and statistically multiplexing the transmission requests of various stations contending to access the channel. The performance of IEEE 802.11 degrades in Ad hoc networks because of the presence of hidden and exposed terminals. To counter these problems, Jagadeesan et al. proposed a new MAC protocol called Interleaved Carrier Sense Multiple Access (ICSMA) Protocol for Ad hoc wireless networks. The performance of ICSMA was compared with single channel 802.11 MAC protocol and with 802.11 MAC protocol over two channels with half the bandwidth through extensive simulation studies. Results showed that ICSMA performed better with respect to throughput, access delay, throughput fairness, and delay fairness when compared with IEEE 802.11.

- **A new class of collision prevention MAC protocols for wireless ad hoc networks** [135]

  You et al. investigated a new class of collision-prevention MAC protocols, called Carrier Sense Multiple Access with Collision Prevention (CSMA/CP), for wireless ad hoc networks. The authors proposed a collision-free MAC protocol called BROADEN based on CSMA/CP. BROADEN is a distributed MAC protocol that could achieve 100% collision-free transmissions in both the control channel and data channel in multihop ad hoc networks. Furthermore, BROADEN could solve the hidden, exposed, and moving terminal problems at the same time. It also improved the performance of previous MAC protocols in terms of average packet delay and network throughput. Moreover, the protocol effectively supported quality-of-service (QoS) provisioning based on prioritization and reservation.

- **A novel topology-blind fair medium access control for wireless LAN and ad hoc networks** [136]

  Fang and Bensaou introduced a new backoff mechanism for IEEE 802.11 which aimed to achieve fair channel access without knowledge of the network topology. By adjusting a time interval and the contention window dynamically, the algorithm aimed to approach the optimal equilibrium where the time interval was the minimum possible such that every node that faced the same contention successfully sent only one packet per such interval.
The authors showed how this algorithm could be modeled as game and use game theoretic arguments to prove the existence and uniqueness of the equilibrium as well as convergence of the algorithm to this equilibrium.

- Collision-free operation in ad hoc carrier sense multiple access wireless networks [137]
  Papachristou and Pavlidou proposed a method of avoiding collisions by using busy energy bursts. The algorithm used was based on the 802.11 standard and depended only on the assumption that each node could hear the transmissions of all other nodes. Collisions were avoided by transmitting short sequences of energy bursts without the need of any further communication between nodes contending for the use of the channel. The proposed method provided better average packet delays also as higher maximum system loads than conventional CSMA/CA. In addition to this, it rendered the use of acknowledgment packets unnecessary.

- A new MAC algorithm based on reservation and scheduling for energy-limited ad-hoc networks [138]
  Jin and Cho proposed an energy efficient MAC algorithm based on reservation and scheduling for wireless ad-hoc networks. The authors evaluated the performance of the proposed MAC scheme with respect to the number, of delayed slots, the channel utilization, and the energy efficiency. Then, the authors derived the fair threshold energy level for the pseudo base station (PBS) reselection in the proposed MAC.

- MAC protocol for mobile ad hoc network with smart antennas [139]
  Yang presented a novel MAC protocol for a mobile ad hoc network with smart antennas adaptive beamforming CSMA/CA protocol (ABF-CSMA/CA). In ABF-CSMA/CA, training sequences were transmitted just before request-to-send (RTS) and clear-to-send (CTS) packets, so the temporal reference beamforming could be performed. An improved virtual carrier-sense mechanism was also proposed. In this scheme, every node had two kinds of network allocation vector (NAV) - omnidirectional NAV (oNAV) and beamforming NAV (WAV). Simulation results showed that ABF-CSMA/CA could support smart antennas effectively and provide higher channel utilisation.

- Interference modeling and performance of Bluetooth MAC protocol [140]
  Cordeiro et al. employed a signal capture model to study the piconet MAC performance, taking inter-piconet interference into consideration. This model led to several important mathematical relationships for Bluetooth networks, including successful packet transmission probability. Furthermore, the model and anticipated throughput were validated using extensive simulation. These results indicated that Bluetooth throughput was affected by multiple piconet interference.
Geographic random forwarding (geraf) for ad hoc and sensor networks: energy and latency performance [141]
Zorzi and Rao studied a novel forwarding technique based on geographical location of the nodes involved and random selection of the relaying node via contention among receivers. The authors provided a detailed description of a MAC scheme based on these concepts and on collision avoidance and reported on its energy and latency performance. A simplified analysis was given first, some relevant trade-offs were highlighted, and parameter optimization was pursued. Further, a semi-Markov model was developed which provides a more accurate performance evaluation. Simulation results supporting the validity of our analytical approach were also provided.

Distributed on-demand address assignment in wireless sensor networks [142]
Schurgers et al. proposed a novel scheme for a MAC address assignment. The two key features which made the approach unique were the exploitation of spatial address reuse and an encoded representation of the addresses in data packets. To assign the addresses, the authors developed a purely distributed algorithm that relied solely on local message exchanges. Other salient features of the approach were the ability to handle unidirectional links and the excellent scalability of both the assignment algorithm and address representation. In typical scenarios, the MAC overhead was reduced by a factor of three compared to existing approaches.

Performance of ad hoc wireless networks with Aloha and PR-CSMA MAC protocols [143]
Ferrari and Tonguz analyzed bit error rate (BER) performance and connectivity characteristics of multi-hop ad hoc wireless networks under a circuit-switched network communication scheme characterized by the creation of a multihop communication route, through intermediate relay nodes, for each source-destination pair. The proposed transmission scheme was packetized yet it did not employ retransmissions: in this sense, it could be considered as a hybrid scheme between circuit switching and packet switching. The ideal limiting performance under the assumption of no inter-node interference (INI) was evaluated. In particular, the concept of minimum spatial energy density was introduced, and quantified with a precise expression in the case of uncoded binary phase shift keying (BPSK) transmission. A realistic scenario with INI was then considered, and two different medium access control (MAC) protocols were proposed: Aloha and ”per-route” carrier sense multiple access (PR-CSMA). In both cases, the BER performance was analyzed. Results showed that MAC and physical layers were strictly interrelated, and designing one without considering the other might lead to wrong choices in ad hoc wireless network design.

A Variable-radius Multichannel MAC protocol for High-Throughput Low-Power Hetero-
geneous Ad Hoc Networking [144]
Yeh et al. proposed the multichannel variable-radius multiple access (M-VRMA) scheme for power-controlled multichannel medium access control (MAC) in mobile ad hoc networks. The authors proposed the RTS/object-to-sending (OTS)/VP-CTS (ROV) protocol based on M-VRMA, multiple access with lag time, OTS, and VP-CTS for efficient variable-radius supports in heterogeneous ad-hoc networks, without relying on busytone or any mechanisms that required expensive specialized hardware or more than one transceivers per device. The simulation results demonstrated that for the same radio bandwidth, ROV could achieve considerably higher throughput as compared to fixed-radius IEEE 802.11 or previous powercontrolled RTS/CTS protocols without variable-radius supports.

• A priority MAC protocol to support real-time traffic in ad hoc networks [145]
Sheu et al. presented a distributed medium access control protocol that provided multiple priority levels for stations to compete for the wireless channel. One common channel was assumed to be shared by all stations. Stations were assumed to be able to hear each other (i.e., the network is fully connected). The channel was accessed by stations according to their priorities, and for stations with the same priority, they sent frames in a round robin manner. The channel access procedure was divided into three stages: priorities classification period, ID initialization period, and transmission period. Simulation results indicated that the protocol provided high channel utilization and bounded delays for real-time frames.

• A jamming-based MAC protocol to improve the performance of wireless multihop ad-hoc networks [146]
One critical issue in multihop ad-hoc networks is the medium access control (MAC). The IEEE 802.11 MAC protocol is originally designed for fully connected, one-hop ad-hoc networks but not for multihop ad-hoc networks. In addition to the well known hidden-terminal problem, we found that IEEE 802.11 also suffers from an erroneous reservation problem which occurs when RTS-CTS exchange fails but the channel is incorrectly reserved. Ye et al. proposed a jamming-based MAC (JMAC) protocol that was not only free from both the hidden-terminal and the erroneous reservation problems but also allowed more concurrent transmission/receipt activities for stations within each other’s transmission range. The idea behind the JMAC was to separate source stations’ traffic from destination stations’ traffic into different channels (i.e. dividing the shared medium into two channels), and explicitly signaled the channel status by jamming the channels. Simulation results showed that although the channel division incurred some cost, the advantages of being free from the erroneous reservation and the hidden-terminal problems, and the benefits of more concurrent transmissions would compensate the cost and provide higher channel utilization when data frame size was median or large.
Medium access control protocols for wireless mobile ad hoc networks: issues and approaches [147]

Issariyakul et al. presented a comprehensive survey of the medium access control (MAC) approaches for wireless mobile ad hoc networks. The complexity in MAC design for wireless ad hoc networks arose due to node mobility, radio link vulnerability and the lack of central coordination. A series of studies on MAC design has been conducted in the literature to improve medium access performance in different aspects as identified by the different performance metrics. Tradeoffs among the different performance metrics (such as between throughput and fairness) dictate the design of a suitable MAC protocol. The authors compared the different proposed MAC approaches, identified their problems and discussed the possible remedies. The interactions among the MAC and the higher layer protocols such as routing and transport layer protocols were discussed and some interesting research issues were also identified.
Chapter 9

Multiple Access

- A novel multiple access protocol for mobile ad hoc networks with smart antennas [148] Yang and Li presented the approach to employ smart antennas in mobile ad hoc network (MANET) nodes. An adaptive beamforming CSMA/CA protocol (ABF-CSMA/CA) was used to distribute channel reservation information. Training sequences were transmitted just before RTS and CTS packets based on non-persistent CSMA, so the temporal reference beamforming (TRB) could be performed by the source node and the destination node. An improved virtual carrier-sense mechanism was also proposed to enhance collision avoidance (CA) and obtained efficient space division multiple access (SDMA). Theoretical analysis of channel utilization of the proposed protocol was presented. Analysis and simulations show that ABF-CSMA/CA protocol combining with smart antennas could provide higher channel utilization.

- Receiver-initiated multiple access protocols for spread spectrum mobile ad hoc networks [149] Su et al. proposed two hybrid handshaking schemes based on the receiver-initiated concept and spread spectrum techniques for spread spectrum mobile ad hoc networks. In these schemes, called Receiver-Initiated Multiple Access Common-Transmitter-Based (RIMA.C-T) and Receiver-Initiated Multiple Access Receiver-Transmitter-Based (RIMA/R-T) protocols. The polling node allowed the polled node to transmit a message to the polling node itself first after it acquired a channel successfully. The proposed schemes were the extension of previous works. Under a general analytic model and assumptions, throughput and message delay of the proposed schemes were evaluated. Theoretical and simulation results showed that the proposed schemes were evaluated. Theoretical and simulation results showed that the proposed schemes achieved better performance than Multiple Access with Collision Avoidance common-Transmitter-Based (MACA/C-T) and Multiple Access with Collision Avoidance Common-Transmitter-Base (MACA/R-T) pro-
A multiple access collision avoidance protocol for multicast service in mobile ad hoc networks [150]
Lee and Cho proposed a multiple access collision avoidance protocol that combines RTS/CTS with scheduling algorithms to support the multicast routing protocol. The authors avoided collision by including additional information in the RTS. The proposed scheme, together with extra benefits, such as power saving, reliable data transmission and higher channel utilization compared with CSMA or multiple unicast, enabled the support of multicast services in mobile ad hoc networks.

User-dependent perfect-scheduling multiple access (UPMA) protocol in wireless multihop mobile ad hoc networks [151]
Based on the idea of contention reservation and polling, Liu et al. described a user-dependent perfect-scheduling multiple access (UPMA) protocol for supporting node mobility and multihop architecture. In the protocol, only the nodes having packets to send contended to use the channel and the nodes without traffic transmission were immediately deleted from the polling list, thus it improved channel utilization greatly. Moreover, a collision avoidance and resolution protocol was proposed to guarantee a node to access the channel rapidly.

A time space division multiple access (TSDMA) protocol for multihop wireless networks with access points [152]
Yeh et al. proposed time division multiple access with circular reservation (TDMA/CR), a time/space division multiple access (TSDMA)-based medium access control (MAC) protocol for wireless mobile networks with control units, including wireless LANs, cellular networks with ad hoc relaying capability, and ad hoc networks with access points or clusterheads. Different from the MAC protocol of IEEE 802.11, TDMA/CR was centralized and could utilize the computation capability of base stations or access points to increase network throughput, reduce latency, and provide QoS guarantees. The authors evaluated the performance of TDMA/CR and showed that the utilization achievable by the wireless-tree (or splitting) channel access mechanisms of TDMA/CR was about 40% to 46% and the channel access delay was small and bounded. Moreover, TDMA/CR could achieve considerably higher throughput (e.g., by a factor of about 3 or higher) due to its support for variable-radius transmissions in ad hoc wireless networks.

Multiple access for 60 GHz mobile ad hoc network [153]
Garnier et al. analyzed the suitability of various multiple access schemes for a 60 GHz mobile ad hoc network. The investigated techniques included multi-carrier modulation (OFDM-TDMA), the spectrum spreading method (DS-CDMA) and the combined
schemes (MC-CDMA, MC-DS-CDMA) benefiting from the advantages of both techniques. The comparison between these different multiple access schemes was focused on two aspects: (i) sensitivity to phase noise; the large available bandwidth around 60 GHz is very suitable for transmission of high data rate in indoor environments, but one issue in the 60 GHz band is the design of oscillators with moderate phase noise; (ii) robustness to imperfect power control; ad hoc networks consist of a set of mobile terminals communicating among themselves without any central controller; radio resource management has to be conducted in a distributed way and the power control is inherently imperfect.

- Adaptive acquisition multiple access protocol in wireless multihop mobile ad hoc networks
  Liu et al. presented a new multiple access control (MAC) protocol called adaptive acquisition multiple access with common-transmission channel assignment (AAMA-CT) and its improved one (AAMA-ICT) for wireless multihop mobile ad hoc networks. In the protocol, every node adaptively chosen a usable channel as its transmission channel in advance in multihop mobile environment and took advantage of request-to-send (RTS) packet transmitted on a common channel to evoke its recipient to complete their communication process on their transmission channels without packet collisions. With this protocol, resource reservation was flexibly and effectively made on multiple channels by half-duplex radios without any help of powerful central controllers and wired backbone networks in an asynchronous fashion. The protocol could solve hidden and exposed terminal problems perfectly as was validated through analysis and simulation results.

- Clique-based randomized multiple access for energy-efficient wireless ad hoc networks
  Flikkema and West described clique-based randomized multiple access (CRMA), a distributed MAC protocol for wireless ad hoc network applications. Of the many objectives in MAC design for this application, CRMA placed strongest emphasis on energy efficiency and reliance only on local (one-hop) connectivity information. CRMA formed collection of nodes, or cliques, separated by one hop, and provided the proactive coordination required for clique members to synchronize their wake-sleep cycles. Each clique selected a slot in the clique’s frame pseudo-randomly, so that no proactive coordination between cliques required. To limit potential access conflicts CRMA could exploit bandwidth via frequency hopping or spread spectrum coding; these also provided robustness to multi-channel radios to increase performance. With a slight amount of additional proactive coordination, CRMA could also employ predictive conflict resolution, wherein clique members predicted access conflicts and resolved them ahead of time.

- Performance analysis of UPMA protocol for wireless multihop mobile ad hoc networks
Based on the concept of contention reservation and polling transmission, Liu et al. described user-dependent perfect-scheduling multiple access (UPMA) protocol for supporting node mobility and multihop architecture in wireless multihop mobile ad hoc network (WMMANET). Based on clustering architecture acquired by self-organizing algorithm, it provided wireless access in a WMMANET with any kinds of topologies. On the other hand, the problem of intercluster traffic relay was sufficiently designed for nodes only having one set of half-duplex transceiver. In the protocol, channel utilization was improved greatly with the help of appropriate arrangement scheme between access period and polling period and any active nodes were guaranteed to access channel rapidly by means of an effective collision avoidance and resolution protocol. Moreover, the authors provided performance analysis on its throughput, delay and message dropping probability. Finally, the analytical results were shown to validate the effectiveness of the proposed protocol.

- A reservation-based multiple access protocol with collision avoidance for wireless multihop ad hoc networks [157]
  Liu et al. proposed a flexible and effective adaptive acquisition collision avoidance (AACA) multiple access protocol. It integrated the concept of multichannel and random reservation with piggyback to effectively solve hidden terminal and exposed terminal problems caused by the multihop architecture. In the protocol, every node adaptively reserved an idle traffic channel by request-to-send and clear-to-send (RTS/CTS) dialogue on the common channel. After successful reservation, the packet transmissions of related nodes were not interrupted by other nodes. The protocol could use any number of channels. It performed better than the single channel RTS/CTS protocol under the assumption of the same total bandwidth if the number of the channels was not too large.

- Dual busy tone multiple access (DBTMA)-a multiple access control scheme for ad hoc networks [158]
  Haas and Deng proposed a new MAC protocol, termed the dual busy tone multiple access (DBTMA) scheme. The operation of the DBTMA protocol was based on the RTS packet and two narrow-bandwidth, out-of-band busy tones. With the use of the RTS packet and the receive busy tone, which was set up by the receiver, the scheme completely solved the hidden- and the exposed-terminal problems. The busy tone, which was set up by the transmitter, provided protection for the RTS packets, increasing the probability of successful RTS reception and, consequently, increasing the throughput. The authors outlined the operation rules of the DBTMA scheme and analyzed its performance. Simulation results were also provided to support the analytical results. It was concluded that the DBTMA protocol was superior to other schemes that rely on the RTS/CTS
dialogue on a single channel or to those that rely on a single busy tone.
Chapter 10

Capacity

• On the power efficiency of sensory and ad-hoc wireless networks [159]
  Hassibi and Dana considered the power efficiency of a communications channel, i.e., the
  maximum bit rate that could be achieved per unit power (energy rate). For AWGN
  channels, it was well know that power efficiency was attained in the low SNR regime.
  The authors showed that for a random sensory, or ad-hoc, wireless network with \( n \) users
  (nodes), with high probability converging to one as \( n \) grew, the power efficiency scaled
  at least by a factor of \( \sqrt{n} \). In other words, each user in a wireless channel with \( n \) nodes
  could support the same communications rate as a single user system, but by expending
  only \( \frac{1}{\sqrt{n}} \) the energy.

• Energy efficiency and fairness in cooperative wireless ad hoc networks [160]
  Srinivasan et al. addressed the issue of user cooperation in ad hoc networks. The authors
  assumed that nodes were rational, i.e. their actions were strictly determined by self-
  interest, and that each node was associated with a minimum lifetime constraint. Then,
  the optimal throughput that each node should receive was able to be determined, and was
  define as the rational Pareto optimal operating point. The authors proposed a distributed
  and scalable acceptance algorithm, which was used by the nodes to decide whether to
  accept or reject a relay request. The algorithm resulted in a Nash equilibrium, and the
  authors proved that the system converged to the rational and optimal operating point.

• Core capacity region of energy-limited wireless ad hoc networks [161]
  Rodoplu and Meng defined the core capacity region of energy-limited wireless ad hoc
  networks and showed that it was non-empty under the linear utility model. The main
  motivation for this paper was the question: "Can wireless ad hoc networks grow into
  a single grand wireless network in the future?" The authors answered this question
  by developing a framework in which they incorporated the incentives of users into the
  definition of network capacity.
• Even one-dimensional mobility increases ad hoc wireless capacity [162].
  Diggavi et al. showed that the throughput result of Grossglauser et al. [163] still held even when nodes had much more limited mobility patterns. Specifically, the authors considered a model in which each node $i$ was constrained to move on a single-dimensional great circle $G_i$ on the unit sphere. Each node moved randomly along its own circle. The throughput capacity of such a network of course depended on the configuration of the great circles. The main result was that if the locations of the great circles were chosen randomly and independently, then for almost all configurations of such great circles, the throughput per S-D pair could be kept constant as the number of nodes increased. Thus, although each node was restricted to move in a one-dimensional space, the same asymptotic performance was achieved as in the case when they could move in the entire 2-D region.

• On the capacity of regular wireless networks with transceiver multipacket communication [164].
  In a wireless network with a sophisticated physical layer, the nodes may be capable of simultaneous multiple packet receptions (MPR) and multiple packet transmissions (MPT). Having multiple reception/transmission codes in a CDMA network, or employing directed antenna arrays are some ways of obtaining MPR/T capability. Although, MPR/T is widely considered in the context of communication with a base station in cellular wireless networks, its effect on the performance of peer-to-peer ad hoc networks is unknown. By developing upper and lower bounds, Mergen and Tong analyzed the effect of physical layer MPR/T capability on the capacity of regular wireless networks. The obtained bounds gave the exact capacity value if the nodes did not have MPT but have MPR.

• On the capacity of wireless relaying [165].
  Host-Madsen considered wireless relaying: one or more nodes in a wireless (ad-hoc) network assisted other nodes in their transmission by partially retransmitting messages. A characteristic of wireless relays is that they could not transmit and receive simultaneously at the same frequency. The author derived new upper and lower bounds for the capacity of this wireless relay channel. The author then applied these result to a 4 terminal network, and showed that the gain (considering outage capacity) of using wireless relaying was of the order of 8-9 dB.

• Capacity regions for wireless ad hoc networks [166].
  Toumpis and Goldsmith defined and studied capacity regions for wireless ad hoc networks with an arbitrary number of nodes and topology. These regions described the set of achievable rate combinations between all source-destination pairs in the network under various transmission strategies, such as variable-rate transmission, single-hop or multihop routing, power control, and successive interference cancellation (SIC). Multihop cellular
networks and networks with energy constraints were studied as special cases. With slight modifications, the developed formulation could handle node mobility and time-varying flat-fading channels. Numerical results indicated that multihop routing, the ability for concurrent transmissions, and SIC significantly increased the capacity of ad hoc and multihop cellular networks. On the other hand, gains from power control were significant only when variable-rate transmission was not used. Also, time-varying flat-fading and node mobility actually improved the capacity. Finally, multihop routing greatly improved the performance of energy-constraint networks.

- Capacity bounds for ad-hoc networks using directional antennas [167]
  Directional antennas can be useful in significantly increasing the capacity of wireless ad hoc networks. With directional antennas, independent communications between nodes can occur in parallel, even if the nodes are within range of each other. However, mutual interference by simultaneous transmissions limits the maximum number of such concurrent communications. Furthermore, it poses bounds on the amount of capacity gain one can achieve by using directional antennas instead of omni-directional ones. These bounds depend on the specific antenna type and its parameters, as well as higher layer protocol requirements. Spyropoulos and Raghavendra calculated interference-based capacity bounds for a generic antenna model as well as a real-world antenna model and analyzed how these bounds were affected by important antenna parameters like gain and beamwidth.

- On the connectivity in finite ad hoc networks [168]
  Desai and Manjunath analyzed finite ad hoc networks. With the standard assumption of uniform distribution of nodes in \([0, z]\), where \(z > 0\), for a one-dimensional network, the author obtained the exact formula for the probability that the network was connected. The author then extended this result to find bounds for the connectivity in a two-dimensional network in \([0, z]^2\).

- Mobility increases the capacity of ad hoc wireless networks [169]
  The capacity of ad hoc wireless networks is constrained by the mutual interference of concurrent transmissions between nodes. Grossglauser and Tse studied a model of an ad hoc network where \(n\) nodes communicated in random source-destination pairs. These nodes were assumed to be mobile. The authors examined the per-session throughput for applications with loose delay constraints, such that the topology changed over the time-scale of packet delivery. Under this assumption, the per-user throughput could increase dramatically when nodes were mobile rather than fixed. This improvement could be achieved by exploiting a form of multiuser diversity via packet relaying.

- The nominal capacity of wireless mesh networks [170]
  Wireless mesh networks are an alternative technology for last-mile broadband Internet
access. In WMNs, similar to ad hoc networks, each user node operates not only as a host but also as a router; user packets are forwarded to and from an Internet-connected gateway in multihop fashion. The meshed topology provides good reliability, market coverage, and scalability, as well as low upfront investments. Despite the recent startup surge in WMNs, much research remains to be done before WMNs realize their full potential. Jun and Sichitiu tackled the problem of determining the exact capacity of a WMN. The key concept the authors introduced to enable this calculation was the bottleneck collision domain, defined as the geographical area of the network that bounds from above the amount of data that could be transmitted in the network. The authors showed that for WMNs the throughput of each node decreases as $O(1/n)$, where $n$ was the total number of nodes in the network. In particular, for a given topology and the set of active nodes, the authors provided exact upper bounds on the throughput of any node. The calculation could be used to provision the network, to ensure quality of service and fairness. The theoretical results were validated by detailed simulations.

- Asymptotic capacity bounds for ad-hoc networks revisited: the directional and smart antenna cases [171] Spyropoulos and Raghavendra looked into how directional and smart antennas could affect the asymptotic behavior of an ad-hoc network’s capacity. Specifically, the authors performed a capacity analysis for an ideal flat-topped antenna, a linear phased-array antenna, and a fully adaptive array antenna model. Finally, the authors explained how an ad-hoc network designer could manipulate different antenna parameters to mitigate the scalability problem of ad-hoc networks.

- Throughput capacity of random ad hoc networks with infrastructure support [172] Kozat and Tassiulas considered the transport capacity of ad hoc networks with a random flat topology under the present support of an infinite capacity infrastructure network. Such a network architecture allowed ad hoc nodes to communicate with each other by purely using the remaining ad hoc nodes as their relays. In addition, ad hoc nodes could also utilize the existing infrastructure fully or partially by reaching any access point (or gateway) of the infrastructure network in a single or multi-hop fashion. Using the same tools in [173], the authors showed that the per source node capacity of $\Theta(W/\log(N))$ could be achieved in a random network scenario with the following assumptions: (i) The number of ad hoc nodes per access point was bounded above, (ii) each wireless node, including the access points, was able to transmit at $W$ bits/sec using a fixed transmission range, and (iii) $N$ ad hoc nodes, excluding the access points, constituted a connected topology graph. This was a significant improvement over the capacity of random ad hoc networks with no infrastructure support which was found as $\Theta(W/\sqrt{N\log(N)})$ in [173]. Although better capacity figures might be obtained by complex network coding or
exploiting mobility in the network, infrastructure approach provided a simpler mechanism that had more practical aspects. The authors also showed that even when less stringent requirements were imposed on topology connectivity, a per source node capacity figure that was arbitrarily close to $\Theta(1)$ could not be obtained. Nevertheless, under these weak conditions, the authors could further improve per node throughput significantly.
Chapter 11

Performance Analysis

• Performance of UTRA TDD ad hoc and IEEE 802.11b in vehicular environments [174]
  The FleetNet project aims at the development of a wireless ad hoc network for Inter-Vehicle Communications (IVC). As a basis for the air-interface, the framework of the UMTS Terrestrial Radio Access Time Division duplex (UTRA TDD) has been selected as the most promising candidate. Since UTRA TDD was developed for operation in a cellular network structure, modifications are required to enable mobile modes to communicate in ad hoc mode without the existence of base stations. In particular, this comprises changes to physical (PHY) layer, Medium access control (MAC) and Radio Resource Management (RRM). Ebner et al. focused on the PHY layer of the air-interface and the resulting challenges in highly dynamic vehicular environments. The performance of the UTRA TDD ad hoc mode was assessed and compared to the IEEE 802.11b standard using link-level simulations. Results indicated that the UTRA TDD ad hoc PHY outperformed IEEE 802.11b in a typical highway scenario with very large relative velocities. In urban traffic environments with strong multipath propagation, IEEE 802.11b was not able to meet the required performance in terms of packet losses.

• Wireless LAN performance under varied stress conditions in vehicular traffic scenarios [175]
  Singh et al. assessed the performance of a wireless local area network in different vehicular traffic and mobility scenarios. The network throughput and the quality of the wireless communication channel, measured on IEEE 802.11b compliant equipment, were observed to degrade with increasingly stressful communication scenarios. The test scenarios were varied by conducting the experiments under different vehicular mobility, peer-distance and driving environment conditions. The authors presented results that could facilitate development of efficient applications for inter-vehicular communication. The authors also suggested optimization measures through aggression control via variations in packet size.
• Performance analysis of ad hoc wireless LANs for real-time traffic [176]

Eshghi and Elhakeem proposed a new performance model for the IEEE 802.11 WLAN in ad hoc mode. The model was based on the presentation of the system with a pair of one-dimensional state diagrams which could easily accommodate variations of many input parameters. The corresponding state variables were contention window size and buffer occupancy of each user in the system. The input parameters considered were: packet fragmentation factor, buffer size, and maximum allowable number of retransmissions. However, the approach taken was capable of ingesting many other probable parameters of interest. System performance criteria under study were: throughput, delay, and probability of fail to deliver. The last two were crucial for real-time applications.

• Performance of iCAR systems: a simplified analysis technique [177]

Yanmaz et al. presented a simplified analysis technique for the integrated cellular and Ad hoc relay (iCAR) systems. First, a simple two-cell system was analyzed using a multi-dimensional Markov-chain. The performance metric employed was the call blocking probability of each cell in the system. To this end, first a closed-form expression for the call blocking probability in the two-cell system was provided. Then, it was shown that these closed-form expressions could be used to analyze more practical systems. The accuracy of the developed simple analytical expressions was checked and verified by comparing the results predicted by these analytical expressions with simulation results.

• Topological performance of mobile backbone based wireless ad hoc network with unmanned vehicles [178]

A hierarchical structure for ad hoc wireless networks has been recently introduced, which classifies nodes into two categories: backbone capable nodes (BCNs) and regular nodes (RNs). BCNs are better equipped, have higher capacities, and have the ability to operate at multiple power levels and employ multiple radio modules. Under our protocol, identified as TBONE, when a BCN is elected to function as a backbone node (BN), it uses its high power link to communicate with other BNs, thus forming a backbone network (Bnet). To access the network, each RN or BCN must associate itself with a nearby BN (if any). The BN manages transmissions across its access network (Anet), whereby messages are transmitted to/from the BN and among Anet members at lower power levels. The protocol dynamically initiates and maintains the configuration and association functions of such a mobile backbone network (MBN) under nodal mobility, topological changes and traffic flow variations. Unmanned vehicles (UVs) are further employed to aid in maintaining the connectivity of the MBN as well as to upgrade the network capacity when required to sustain real-time and messaging flows that demand quality-of-service (QoS) performance assurance. Rubin et al. presented the performance features of this protocol, evaluating the number of nodes that were activated as BNs, characterizing the
extent to which the system covered its client mobile station using its prescribed BCNs, and presenting the rate of various protocol interactions as a function of the mobility speed of nodal users. The authors also evaluated the impact of employed UVs on the system’s connectivity and coverage features.

• Analyzing interaction between network protocols, topology and traffic in wireless radio networks [179]

Barrett et al. studied the interaction between communication protocols, network topology and packet traffic in wireless static radio networks. A particular interest was to empirically characterize the effect of interaction between the routing layer and the MAC layer on overall system performance. Three well-known MAC protocols: 802.11, CSMA and MACA were considered. Similarly three recently proposed routing protocols: AODV, DSR and LAR scheme 1 were considered. The performance of the protocols was measured with regard to three important parameters: (i) number of packets received, (ii) average latency of each packet and (iii) long term fairness. The authors used a simple statistical technique based on ANOVA (analysis of variance), to characterize the effect of interaction between protocols and various input parameters on network performance. This technique was of independent interest and could be utilized in other simulation studies. Using this methodology, the authors concluded that different combinations of routing and MAC protocols yielded varying performance under varying network topology and traffic situations. The results showed that no combination of routing protocol and MAC protocol was the best over all situations. An important implication of the study was that the performance analysis of protocols at a given level in the protocol stack needed to be studied not locally in isolation but as a part of the complete protocol stack.

• Evaluating the communication performance of an ad hoc wireless network [180]

Toh et al. evaluated the practicality of realizing an ad hoc wireless network and investigated on performance issues. Several mobile computers were enhanced with ad hoc routing capability and were deployed in an outdoor environment and communication performance associated with ad hoc communications were evaluated. These computers periodically sent beacons to their neighbors to declare their presence. The authors examined the impact of varying packet size, beaconing interval, and route hop count on route discovery time, communication throughput, end-to-end delay, and packet loss. The authors also performed mobility experiments and evaluated the route reconstruction time incurred. File transfer times associated with sending information reliably (via TCP) over multihop wireless links were also presented. The experimental results obtained revealed that it was feasible to augment existing wireless computers with ad hoc networking capability. End-to-end performance in ad hoc routes were less affected by beaoning intervals than packet size or route length. Similarly, communication throughput was more
dependent on packet size and route length with the exception at very high beaconing frequencies. Packet loss, on the other hand, was not significantly affected by packet size, route length or beaconing frequency. Finally, route discovery time in ad hoc wireless networks were more dependent on channel conditions and route length than variations in beaconing intervals.

- A performance comparison between ad hoc and centrally controlled CDMA wireless LANs [181]

Bai and Tong presented a performance comparison between two types of code-division multiple-access wireless local area networks: centrally controlled and ad hoc networks. Based on a finite-population model, the network throughput, the average packet delay, and the network first exit time were derived for both systems. Two aspects of the performance comparison were addressed: (1) the comparison between the centrally controlled and the ad hoc architecture; and (2) the impact of spreading gain and error control coding on both systems. The efficiency of bandwidth utilization was investigated by normalizing the network performance with respect to the consumed bandwidth.

- Performance analysis of random database group scheme for mobility management in ad hoc networks [182]

Li et al. presented the performance of a distributed mobility management scheme, the Randomized Database Group (RDG), for mobile ad hoc networks. In this scheme, databases were used to store the location of the network nodes and to manage the mobility of nodes. When a mobile’s location changed, a number of randomly selected databases were updated. When a mobile’s location was needed, such as upon a call arrival, a number of randomly selected databases were queried. A number of different RDG query schemes were studied and their performance were compared. In particular, the optimum update-group size and the query-group size were found. The authors also presented the probability of the first query being successful and the average query delay to find the mobile’s location. Finally, the authors estimated the cost of implementing the RDG scheme as a function of different number of databases.
Chapter 12

QoS

• Asymptotic delay in random wireless networks [183]
  Ahmed and Pottie presented an estimate of the average delay experienced by data bits transported through randomly distributed nodes forming a multi-hop wireless network as an order of the number of nodes in the network. The expected asymptotic delay observed per bit, from a source to a destination node, essentially averaged to the order of $O(\sqrt{n})$, for $n$ nodes in the network.

• Scheduling Based on Message in Ad Hoc Networks [184]
  Tian et al. presented a new scheduling strategy that considered not only the length of the remaining message in queue but also the original message length when it scheduled packets. Simulation results indicated that substantial performance improvement in end-to-end message delay could be obtained without adversely affecting the network message throughput. No additional communication overhead was needed and the computational overhead was also not high.

• Adaptive EDCF: enhanced service differentiation for IEEE 802.11 wireless ad-hoc networks [185]
  Romdhani et al. described an adaptive service differentiation scheme for QoS enhancement in IEEE 802.11 wireless ad-hoc networks. The approach, called adaptive enhanced distributed coordination function (AEDCF), was derived from the new EDCF introduced in the IEEE 802.11e standard. The scheme aimed to share the transmission channel efficiently. Relative priorities were provisioned by adjusting the size of the contention window (CW) of each traffic class taking into account both applications requirements and network conditions. The authors evaluated through simulations the performance of AEDCF and compared it with the EDCF scheme proposed in the 802.11e. Results showed that AEDCF outperformed the basic EDCF, especially at high traffic load conditions. Indeed, the scheme increased the medium utilization ratio and reduced for more than 50% the
collision rate. While achieving delay differentiation, the overall goodput obtained was up to 25% higher than EDCF. Moreover, the complexity of AEDCF remained similar to the EDCF scheme, enabling the design of cheap implementations.

- Queuing delay performance of the integrated cellular and ad hoc relaying system [186]
The integrated cellular ad hoc relaying (iCAR) system is a representative heterogeneous wireless system, proposed to address the congestion problem in the wireless networks. Wu et al. presented an analytic model based on Markov chains for the queuing delay performance of iCAR. The results showed that the new call requests in iCAR had a significantly lower queuing delay than that of the conventional cellular system. The analytic model developed in this paper might serve as the guideline for the delay performance evaluation of the next generation heterogeneous wireless systems.

- An analytical model for measuring QoS in ad-hoc wireless networks [187]
Futernik et al. developed an analytical model for evaluating the Quality of Service (QoS) in wireless ad-hoc networks. In doing so it extended the trunking theory concepts to encompass the effect of co-channel interference. Chosen as the QoS figure of merit, the transmission blocking probability, was derived as a function of the number of nodes, the network density and parameters of a Markov chain model for the multiple user channel access protocol.

- A resource-efficient QoS routing protocol for mobile ad hoc networks [188]
The performance of existing QoS routing protocols is often constrained with high control traffic and database maintenance overhead. We observe that by proper coupling of nodal mobility and location information, better QoS support can be achieved with reduced control traffic and database requirements. De et al. investigated the performance of a location-aware QoS routing protocol, called trigger-based distributed routing (TDR), for mobile ad hoc networks. In this protocol, the nodal database size was reduced by maintaining only local neighborhood information, and route maintenance control overhead was kept low by maintaining only one route at a time for a session. Distributed rerouting control and directed alternate route discovery helped reduce the rerouting control overhead and perform quicker route repair. Moreover, rerouting based on signal degradation history made it possible to minimize the in-session route failure. The evaluation showed that the TDR protocol had significantly better QoS support and reduced overhead requirements compared to the existing QoS routing protocols in ad hoc networks.

- A survey on quality-of-service support for mobile ad hoc networks [189]
The general field of mobile ad hoc networking is still in its infancy. Particularly, the challenge of providing Quality-of-Service (QoS) support for ad hoc networks is an open problem and remains relatively uncharted territory. Providing a complete QoS solution for
the ad hoc networking environment requires the interaction and cooperation of several components. These components include: (1) a QoS routing protocol, (2) a resource reservation scheme and (3) a QoS capable medium access control (MAC) layer. Perkins and Hughes presented a survey of the current research that had addressed each of these components in the context of ad hoc networks. This work was intended to provide a broad and comprehensive view of the various components and protocols required to provide QoS support in computer networks, focusing primarily on ad hoc networks. First, the authors introduced the unique characteristics of mobile ad hoc networks, which distinguishing this new network architecture from traditional infrastructured wired and wireless networks (i.e. cellular-based networks). The authors also discussed the impact of these characteristics on QoS provisioning. Next, the authors described the first QoS model proposed for mobile ad hoc networks and its relationship to QoS models proposed for the Internet. The authors then presented a review of the proposed algorithms for each QoS component (e.g. QoS routing, resource reservation and the MAC layer).
Chapter 13

Coverage

• Average connectivity properties of wireless ad hoc networks [190]
  Shu et al. considered the average radio coverage area size of a connected cluster $\Omega(\alpha, r)$ in a uniformly randomly deployed wireless network over a $D$-dimensional infinite field ($D \geq 1$), where $r$ is the radio distance, and $\alpha/\gamma$ the nodal deployment density. The authors showed that $\Omega_N(y) \equiv \alpha \Omega(\alpha, r)$ was a function of $y \equiv \alpha \Phi(r)$ only, where $\Phi(r)$ denoted the volume of a sphere with radius $r$. The authors provided an explicit form of $\Omega_N(y)$ for arbitrary $D$ as the sum of three terms, dominated by one that exhibits exponential behavior. For $D = 1$, the authors showed that $\Omega_N(y) = \exp(y/2) + (y/2) - 1$. The simulations validated their 1-d solution, and showed that the exponent for 2-d deployment was smaller than $y$.

• Coverage in wireless ad hoc sensor networks [191]
  Sensor networks pose a number of challenging conceptual and optimization problems such as location, deployment, and tracking. One of the fundamental problems in sensor networks is the calculation of the coverage. In Meguerdichian et al. (2001), it is assumed that the sensor has uniform sensing ability. Li et al. provided efficient distributed algorithms to optimally solve the best-coverage problem raised in the above-mentioned article. In addition, the authors considered a more general sensing model: the sensing ability diminished as the distance increases. As energy conservation was a major concern in wireless (or sensor) networks, the authors also considered how to find an optimum best-coverage-path with the least energy consumption and how to find an optimum best-coverage-path that traveled a small distance. In addition, the authors justified the correctness of the method proposed above that used the Delaunay triangulation to solve the best coverage problem and showed that the search space of the best coverage problem could be confined to the relative neighborhood graph, which could be constructed locally.

• Optimal coverage paths in ad-hoc sensor networks [192]
Mehta et al. discussed the computation of optimal coverage paths in an ad-hoc network consisting of \( n \) sensors. Improved algorithms, with a preprocessing time of \( O(n \log n) \), to compute a maximum breach/support path \( P \) in optimal \( O(|P|) \) time or the maximum breach/support path \( P \) in optimal \( O(|P|) \) time or the maximum breach/support value in \( O(1) \) time were presented. Algorithms for computing a shortest path that had maximum breach/support were also provided. Experimental results for breach paths showed that the shortest path length was on the average 30% less and was not much worse than the ideal straight line path. For applications that required redundancy (i.e., detection by multiple sensors), a generalization of Voronoi diagrams allowed us to compute maximum breach paths where breach was defined as the distance to the \( k \)th nearest sensor in the field.
Chapter 14

Link Quality

- Ad Hoc Wireless Networks with Noisy Links [193]
  Models of ad-hoc wireless networks are often based on the geometric disc abstraction: transmission is assumed to be isotropic, and reliable communication channels are assumed to exist (apart from interference) between nodes closer than a given distance. In reality, communication channels are unreliable and communication range is generally not rotationally symmetric. Booth et al. examined how these issues affect network connectivity in this paper.

- Signal strength-based link stability estimation in ad hoc wireless networks [194]
  Lim et al. presented an enhanced link stability estimation model for ad hoc wireless networks. In the comparison of three models, the routing with the proposed model found a route that had the longest lifetime with little increase in hop-length. Especially, the route had two times longer lifetime than the shortest path route.

- Understanding link quality in 802.11 mobile ad hoc networks [195]
  Gaertner and Cahill showed that the communication quality of current 802.11 ad hoc networks was low, and that users could experience strong fluctuations in link quality as a result. They identified key factors that caused these fluctuations and derived implications for application development. In particular, applications must tolerate frequent disconnections, network partitioning, and latency variations that were far more severe than in conventional networks.

- Channel modeling for ad hoc mobile wireless networks [196]
  Wang and Cox showed a way to simulate small-scale and large-scale fading on links in an ad hoc network and presented simulation results for a multipath shadowed outdoor environment. The authors studied fundamental discrepancies between ad hoc and cellular networks and found that link performance was worse for the ad hoc case, but, more
interestingly, the performance gap shrank with "increased mobility".

Chapter 15

Multipath

- A neighbor-table-based multipath routing in ad hoc networks [197]
  Yao et al. proposed a neighbor-table-based multipath routing (NTBMR) protocol to track the dynamic topology changes. Distinguished from prior work on multipath protocols employing disjoint paths, NTBMR did not require the routes to be disjoint. In order to verify the different capabilities against dynamic topology changes for disjoint and non-disjoint multipath routing, the authors made an attempt to analyze their route reliabilities. Theoretical analysis revealed that non-disjoint multipath routing had higher route reliability when the wireless links were unreliable. In NTBMR scheme, the authors also presented a technique to estimate the mean and variance of the lifetime of a wireless link, which could be used to aid route discovery and maintenance. Simulation results showed that our multipath routing scheme was relatively robust in an environment with frequent topology changes and could improve the end-to-end delay and packet delivery ratio performance substantially compared to unipath routing.

- A cognitive framework for performance/resilience optimized multipath routing in networks with unstable topologies [198]
  Marbukh proposed a framework for optimized multipath routing in a wireless network with frequently changing topology. The framework attempted to minimize losses (regrets) resulted from uncertainty in the network state at the point of making the routing decision. The framework yielded the optimal route mixture in the neighborhood of the ”best” route. This framework naturally allowed for the game theoretic interpretation with routing algorithm making a feasible routing decision and adversarial environment selecting a feasible, i.e., consistent with available information, network state. The optimal route mixture was identified with (generally mixed) Nash routing strategy in the corresponding game.

- An efficient strategy in sensor networks [199]
Due to limited functionalities and potentially large number of sensors, conventional routing strategies proposed for distributed control applications (such as mobile ad hoc networks) are not directly applicable in wireless sensor networks. De et al. proposed a novel mesh multipath routing (M-MPR) with selective forwarding of packets. The evaluation showed that M-MPR achieved much improved throughput performance over conventional disjoint multipath routing, with comparable power consumption and receiver complexity. The authors also showed that for comparable throughput, M-MPR achieved better load distribution and required lesser route maintenance overhead with respect to packet forwarding along a preferred route.

- An adaptive framework for multipath routing via maximally zone-disjoint shortest paths in ad hoc wireless networks with directional antenna [200]
  Saha et al. proposed a notion of zone-disjoint routes in wireless medium where paths were said to be zone-disjoint when data communication over one path would not interfere with data communication in other path. The notion of zone-disjointness was used as route selection criteria. However, zone-disjointness alone was not sufficient for performance improvement. If the path-length (number of hops) were large, that would increase the end-to-end delay even in the context of zone-disjointness. So, it was imperative to select maximally shortest paths. However, getting zone-disjoint or even partially zone-disjoint routes in ad hoc network with omni-directional antenna was difficult, since the transmission zone of each node was larger compared to that with directional antenna. Hence, one way to reduce this transmission zone of a node was to use directional antenna. The authors investigated the effect of directional antenna on zone-disjoint multipath routing and evaluated its effectiveness in QualNet Network Simulator.

- Analysis of Multipath Routing - Part I: The Effect on the Packet Delivery Ratio [201]
  Tsirigos and Haas developed an analytical framework for evaluating multipath routing in mobile ad hoc networks. The instability of the topology (e.g., failure of links) in this type of network due to nodal mobility and changes in wireless propagation conditions makes transmission of time-sensitive information a challenging problem. To combat the inherent unreliability of these networks, the authors proposed a routing scheme that used multiple paths simultaneously by splitting the information between a multitude of paths, so as to increase the probability that the essential portion of the information was received at the destination without incurring excessive delay. The scheme worked by adding an overhead to each packet, which was calculated as a linear function of the original packet bits. The resulting packet (information and overhead) was fragmented into smaller blocks and distributed over the available paths. The probability of reconstructing the original information at the destination was derived in an analytical form and its behavior was studied for some special cases. It was shown that, under certain constraints, the packet
dropping probability decreased as the number of used paths was increased.
Chapter 16

Resource Management

- Future mobile broadband wireless networks: a radio resource management perspective [202]
  Future wireless evolution envisages high rates, low hierarchy in the network architecture, antenna array processing, multiple access modes and multihop operation as part of the system concept. To exploit the increased capabilities of the systems in conception, efficient resource management strategies need to be developed. Periyalwar et al. examined the key aspects of the evolution which impact radio resource management for the mobile broadband wireless network, and emphasized the areas that needed to be addressed for servicing mobile users with varying quality of service requirements.

- A channel assignment scheme for FDMA based wireless ad hoc networks in Rayleigh fading environments [203]
  Kulkarni and Srivastava addressed the problem of allocating spatially reused frequency channels in ad hoc networks to satisfy data rate constraints on various links. The data rate requirement of each link was satisfied by using adaptive modulation. Power control was used to maintain the required signal to interference and noise ratio (SINR) in the presence of interference, which was caused due to frequency reuse. The objective was to minimize the total transmitted power over the entire network while satisfying the data rate requirement of each link. The authors showed that this problem was a hard optimization problem and presented a heuristic algorithm. The simulation results showed that our algorithm results in an efficient assignment of frequencies and transmitter power levels in terms of the energy required for transmitting each bit of information. The results also demonstrated that the algorithm outperformed existing techniques.

- Combined routing, channel scheduling, and power control in packet radio ad hoc networks with cellular overlay [204]
  St-Jean et al. presented the development of a framework for a high capacity wireless
network for Internet applications. By replacing some of the network nodes with wireless routers, the authors formed a wireless multihop network overlaid on a cellular structure. The authors addressed the problem of jointly optimizing routing, channel scheduling, and power control to maximize the total system throughput under a transmit power constraint. The authors demonstrated that by considering the interrelationship among the network, data link, and physical layers, the authors increased the network throughput. The work was based on minimizing a defined objective function which included the cost related to the transmit power for emptying the buffer with a certain amount of information and the selected route to the final destination.

- Efficient dynamic load balancing algorithms using iCAR systems: a generalized framework [205]
  Yanmaz et al. provided a general framework for dynamic load balancing in the integrated cellular and ad hoc relay (iCAR) systems, where the number of hot cells, the location of these hot cells and the traffic distribution in the system was arbitrary. Results showed that the call blocking probabilities of the hot cells could be decreased substantially. Moreover, a threshold traffic, which was a function of the average traffic intensity in the overall system, was specified to determine the hot cells in the system, and the effect of the threshold value on the computational complexity of the dynamic load balancing algorithm was examined and quantified.

- Credit-based fair scheduling in ad hoc wireless networks [206]
  Chao and Liao studied fair scheduling in ad hoc wireless networks. The authors proposed a credit-based mechanism to ensure fairness for best effort flows. Each flow was associated with a credit value, and was scheduled based on the concept of “the less excess in usage value, the higher the transmission priority”. The network was logically partitioned into clusters, each with a scheduler, and an unique code. The schedulers first assigned time slots to mobiles in the affiliated clusters. The mobile scheduled to send at the next time slot then in turn assigned the time slot to a flow. Each scheduler operated independently, and together, they allowed flows in the network to share bandwidth in a fair way. The authors had also performed simulations to validate the proposed mechanism. The results showed that the proposed mechanism provides fair share of bandwidth to all flows, and also improved overall system throughput.

- Distributed call admission control for ad hoc networks [207]
  Valaee and Li introduced a distributed call admission controller for ad hoc networks. The call admission controller was based on service curve provisioning. Service curve reflected the status of network and depended on the number of active nodes, their activity index, and the back-off procedure used for contention resolution. The service curve along with
the aggregated traffic function could be used to calculate maximum delay and maximum backlog. The authors assumed that the call requests were granted if the service curve was bounded below by some non-decreasing deterministic function which was called the universal service curve. The universal service curve was independent of the number of nodes and traffic fluctuation and acted as a worst-case reference curve. All users willing to establish a new connection should compare the performance of network to the universal service curve. A call request was accepted if the true service curve stayed above the universal service curve.

• Joint Scheduling and Power Control for Wireless Ad Hoc Networks [208]
ElBatt and Ephremides introduced a cross-layer design framework to the multiple access problem in contention-based wireless ad hoc networks. The motivation for this study was two fold, limiting multiuser interference to increase single-hop throughput and reducing power consumption to prolong battery life. The authors focused on next neighbor transmissions where nodes were required to send information packets to their respective receivers subject to a constraint on the signal-to-interference-and-noise ratio. The multiple access problem was solved via two alternating phases, namely scheduling and power control. The scheduling algorithm was essential to coordinate the transmissions of independent users in order to eliminate strong levels of interference (e.g., self-interference) that could not be overcome by power control. On the other hand, power control was executed in a distributed fashion to determine the admissible power vector that could be used by the scheduled users to satisfy their single-hop transmission requirements. This was done for two types of networks, namely time-division multiple-access (TDMA) and TDMA/code-division multiple-access wireless ad hoc networks.

• Credit-based slot allocation for multimedia mobile ad hoc networks [209]
Chao and Liao studied resource management for multimedia mobile ad hoc networks (MANET). In particular, The authors focused on providing fair scheduling with quality-of-service (QoS) support for MANET. The authors considered two types of flows: guaranteed and best effort flows. The goal was to satisfy the QoS requirements of guaranteed flows and to provide global fairness for best effort flows. The authors proposed a credit-based fair scheduling mechanism called credit-based slot allocation protocol (CSAP). In CSAP, nodes were logically grouped into clusters, each with a scheduler. Each scheduler assigned time slots to nodes in its cluster based on the first tier algorithm. The node scheduled to sent at the next time slot then in turn assigned the time slot to a relayed flow determined by the second-tier algorithm. Each multihop flow was treated as multiple single-hop flow segments. These segments were then correlated such that a downstream segment would not be allocated a slot unless the upstream segments had all been allocated. The authors evaluated the performance of CSAP by simulations. The results showed that CSAP met
the QoS requirements of guaranteed flows, provided global fairness for best effort flows, and improved overall system throughput.

- A code allocation protocol for maximizing throughput in CDMA based ad hoc networks [210]
  Srivastava et al. considered the problem of allocating variable length orthogonal codes in an ad hoc network based on CDMA. The authors considered a snapshot version of the problem at some instant. It had been proved earlier than even for a static set of communications and topology the problem was intractable. A greedy algorithm was stated to provide a bounded approximation to the throughput maximizing optimal allocation. The authors presented a simple distributed code allocation protocol based on the greedy approximation. Simulation experiments showed the enhanced throughput obtained by our protocol as compared to other code allocation schemes.

- On the connectivity modeling and the tradeoffs between reliability and energy efficiency in large scale wireless sensor networks [211]
  Zhu and Papavassiliou first provided a model that characterizes the corresponding sensor connectivity distribution for a sensor networking system, and based on this model the authors gained some insight about the trade off among the node connectivity, power consumption, data rate, etc. The impact of node connectivity on system reliability was discussed. Furthermore in order to reduce the sensor power consumption the authors analyzed the relationship between periodical sleeping strategies and the achieved power conservation. Several results and tradeoffs among various sleeping strategies, transmission scenarios and power gains, for given connectivity requirements, were also presented and evaluated.

- A distributed joint scheduling and power control algorithm for multicasting in wireless ad hoc networks [212]
  Wang et al. addressed the problem of power control in ad hoc networks supporting multicast traffic. First, the authors presented a distributed algorithm which, given the set of multicast transmitters and their corresponding receivers, provided an optimal solution to the power control problem. The transmit power levels obtained by solving the optimization problem minimized the network power expenditure while meeting the requirements on the SINR at the receivers. Whenever no optimal solution could be found for the given set of multicast transmitters, the authors introduced a joint scheduling and power control algorithm, which eliminated the strong interferers thus allowing the other transmitters to solve the power control problem. The algorithm could be implemented in a distributed manner; however, it provided a sub-optimal solution since it was based on 'local' information. Simulation results showed that the obtained solution was close to the global
optimum, when it existed. when there was no optimal solution, the proposed algorithm tried to maximize the number of successful multicast transmissions.

- On tree-based convergecasting in wireless sensor networks [213] 
  Annamalai et al. showed that we needed a new algorithm for applications, which involved both convergecasting and broadcasting since the broadcast tree might not be efficient for convergecasting. So the authors proposed a heuristic algorithm (convergecasting tree construction and channel allocation algorithm (CTCCAA)), which constructed a tree with schedules assigned to nodes for collision free convergecasting. The algorithm was capable of code allocation (direct sequence spread spectrum (DSSS)/ frequency hopping spread spectrum (FHSS)), in case multiple codes were available, to minimize the total duration required for convergecasting. The authors also showed that the same tree could be used for broadcasting and was as efficient as a tree exclusively constructed for broadcasting.

- Exploiting macrodiversity in dense multihop networks and relay channels [214] 
  Embedded networks of sensors and actuators must operate at extremely low power and use inexpensive single-antenna transceivers. The economics of such systems preclude the use of complex signal processing or antenna arrays at any one device. However, the same economics allows the coverage area to be blanketed with a high density of devices, which results in a rich spatial diversity. This spatial diversity can be exploited by forming a virtual antenna array, which combines observations made at multiple receivers. Valenti and Correal illustrated the potential transmit energy savings that were possible by using such macrodiversity-combining approaches by the analysis and simulation of an idealized system. It concluded by discussing practical issues that must be considered before integrating macrodiversity-combining strategies into actual embedded networks.

- Capacity assignment on asymmetric Bluetooth link [215] 
  Luo et al. used the delay cost function to analyse the capacity assignment for a Bluetooth link. Although it only focused in solving the capacity assignment of a single link, it was also applicable to large-size multi-link and multi-hop networks. It could be extended to generic data networks with asymmetric links.

- Radio resource sharing for ad hoc networking with UWB [216] 
  Cuomo et al. presented the main principles to design a multiaccess scheme based on UWB (Ultra-wideband). The potential of UWB was exploited within a distributed ad hoc wireless system, where the authors described the principles for the definition of a medium-access control (MAC) for mobile computing applications and the authors analyzed the main performance results derived from simulations. A general framework for radio resource sharing was outlined for classes of traffic requiring both elastic-dynamic
and guaranteed-reserved bandwidth. Then, the authors discussed the issue of supporting the proposed radio resource sharing scheme by means of a distributed MAC protocol.

- A multicast congestion control scheme for mobile ad-hoc networks [217]
Peng and Sikdar presented a multi-rate multicast congestion control scheme for Mobile Ad-hoc Networks (MANETs). Not only did the proposed scheme overcome the disadvantages of existing multicast congestion control protocols which prevented them from being used in MANETs, but it also achieved good performance in other aspects such as fairness with TCP, robustness against misbehaving receivers, and traffic stability. Besides achieving the above advantages, the proposed scheme did not impose any significant changes on the queuing, scheduling or forwarding policies of existing networks.

- Stream control in networks with interfering MIMO links [218]
Demirkol and Ingram presented a distributed algorithm, which exploited channel state information (CSI) at the transmitter for determining the maximum number of independent data streams for each transmitting node in a network of interfering multiple-input multiple-output (MIMO) links. Simulated throughputs for two simple network topologies showed that the algorithm yielded nearly optimal stream control. These closed-loop MIMO throughputs were compared to those of open-loop MIMO, with and without optimal stream control, and to the throughput when the links operated in a non-interfering, TDMA fashion.

- Self-coordinating localized fair queueing in wireless ad hoc networks [219]
Distributed fair queueing in a multihop, wireless ad hoc network is challenging for several reasons. First, the wireless channel is shared among multiple contending nodes in a spatial locality. Location-dependent channel contention complicates the fairness notion. Second, the sender of a flow does not have explicit information regarding the contending flows originated from other nodes. Fair queueing over ad hoc networks is a distributed scheduling problem by nature. Finally, the wireless channel capacity is a scarce resource. Spatial channel reuse, i.e., simultaneous transmissions of flows that do not interfere with each other, should be encouraged whenever possible. Luo et al. reexamined the fairness notion in an ad hoc network using a graph-theoretic formulation and extract the fairness requirements that an ad hoc fair queueing algorithm should possess. To meet these requirements, the authors proposed Maximize-Local-Minimum Fair Queueing (MLM-FQ), a novel distributed packet scheduling algorithm where local schedulers self-coordinated their scheduling decisions and collectively achieved fair bandwidth sharing. The authors then proposed Enhanced MLM-FQ (EMLM-FQ) to further improve the spatial channel reuse and limited the impact of inaccurate scheduling information resulted from collisions. EMLM-FQ achieved statistical short-term throughput and delay bounds over the shared
wireless channel. Analysis and extensive simulations confirmed the effectiveness and efficiency of our self-coordinating localized design in providing global fair channel access in wireless ad hoc networks.

- Performance of adaptive bridge scheduling in a scatternet with a slave-slave bridge [220]
  End-to-end packet delays in a Bluetooth scatternet with a Slave-Slave (SS) bridge can be minimized by adjusting the bridge residence times in accordance with traffic intensity and locality. The authors presented two algorithms to do so. One of these used a fixed value of the bridge residence time, while the other adjusted the residence time dynamically according to the instantaneous intensity of inter-piconet traffic. The authors discussed the performance of these algorithms and showed that the adaptive algorithm offers better performance than the fixed residence time one, provided the parameters are chosen appropriately. The authors also considered the stability of both algorithms and showed that they had comparable stability limits.
Chapter 17

Energy Efficiency and Power Control

- Comparison of two wireless ad hoc routing protocols on a hardware test-bed [221]
  Bhandare et al. compared the dynamic source routing (DSR) protocol and their energy aware dynamic source routing protocol (EADSR). The implementation of the routing protocols was carried out using the click modular router infrastructure on laptops with wireless Ethernet cards running Linux. The authors demonstrated the working of both ad hoc routing protocols through their experiments and highlighted the energy efficient behavior of EADSR as compared to DSR.

- Lifetime prediction routing in mobile ad hoc networks [222]
  Maleki et al. presented a lifetime prediction routing protocol for MANETs that maximized the network lifetime by finding routing solutions that minimized the variance of the remaining energies of the nodes in the network. Although this scheme introduced some additional traffic, simulations showed that it improved the network lifetime by about 20-30%.

- Exploring the energy-latency tradeoff of geographic random forwarding for ad hoc and sensor networks [223]
  Zorzi and Rao considered a novel forwarding technique based on collision avoidance and on knowledge of the geographical location of the nodes involved. Selection of the relaying nodes was made randomly via contention among receivers. The authors considered a simplified performance analysis and provide analytical parameter optimization. Comparisons giving evidence of the accuracy of the approximate approach were also provided. The scheme was compared with STEM, and was shown to perform, significantly better for sufficient node density.

- Energy-efficient routing in DSSS ad hoc networks under mean rate constraints [224]
  Jantti and Kim considered a problem of maximizing lifetime of a wireless ad hoc network.
The study started from a system model that considered the signal to interference ratio and incorporated it into a variable data rate on a link. The author found mathematical similarity between the lifetime maximization and the classical power control problem arising in cellular radio systems. With this finding, the author developed an iterative algorithm for lifetime maximization, which was mathematically similar to distributed power control in cellular systems. Numerical examples were included to illustrate how the algorithm could be applied to lifetime maximization. Also the authors got insights how the transmission power of each node could affect the lifetime of an ad hoc network.

- New clustering schemes for energy conservation in two-tiered mobile ad hoc networks [225]
  Ryu et al. proposed two distributed heuristic clustering schemes that would minimize the required transmission power in two-tiered mobile ad hoc networks. Both schemes could be implemented and executed in real time and could be adopted for periodic or event-driven cluster reconfiguration. Scheme performance was simulated and compared with optimum configurations based on the mean transmission power and the call drop rate as performance measures. Numerical results showed that the proposed schemes delivered performance similar to optimum results.

- Kinetic spanning trees for minimum-power routing in MANETs [226]
  Gentile and VanDyck proposed a distributed kinetic spanning tree algorithm for routing in wireless mobile ad hoc networks. Assuming a piecewise linear motion model for the nodes, the sequence of shortest-path spanning trees was determined, valid until the time of the next node trajectory change. By computing the sequence of trees using one execution of the distributed routing algorithm, in contrast to computing the tree for a single time instant, the number of routing messages was substantially reduced. Moreover, the total power required to route through the trees as a function of time was also lower.

- Distributed power control for ad hoc networks with smart antennas [227]
  An IEEE 802.11-based media access control (MAC) protocol was recently proposed for ad hoc network stations using smart antennas. The protocol uses omni-directional RTS/CTS interactions to estimate the channel between sending and receiving stations. The two stations then communicate using beamformed transmission on both ends of the link, at a reduced transmit power. Although large increases in capacity are possible using this approach, the improvements are a strong function of the transmit power reduction, and the optimal value is highly situation dependent. Fahmy et al. introduced a distributed power control mechanism that enabled such networks to achieve dynamically capacity results close to the optimal limits. The approach was to collect interference data at the receivers during DATA/ACK periods, and to communicate this information between the
stations associated with the links in question. The proposed protocol was successful in adapting to different physical situations and the results indicated that capacities could be achieved that were very close to the best static local power control schemes.

- **Power-efficient MAC scheme using channel probing in multirate wireless ad hoc networks** [228]
  Kim and Bambos proposed a MAC scheme for multirate wireless ad hoc networks, extending a power control algorithm called DPC/ALP (distributed power control with active link protection) (see Bambos, N. et al., IEEE/ACM Trans. on Networking, vol.8, no.5, 2000), which allowed a mobile to predict its evolution of SIR by probing the channel for a short time. Using this property, the authors developed an access control scheme called adaptive probing which was capable of deciding the maximum allowable data rate. Contrary to CSMA schemes, which tend to wait for other mobiles to end their transmissions before initiating a new one, adaptive probing could selectively transmit at lower data rates in the presence of multiple active transmissions. As a result, it could lower the transmission delay even in heavily loaded networks, and performed better than standard approaches. Fairness was supported by a flow control mechanism called pipelining, which limited the number of consecutive transmissions of each user. Through a simulation study, the authors showed that the proposed protocol can save power by more than 20 dB in a light network loading, and the delay in a heavy loading was smaller than a quarter of that of high rate IEEE 802.11b (11 Mbps).

- **Comparing the routing energy overheads of ad-hoc routing protocols** [229]
  Bansal *et al.* used simulations to study the comparative routing overheads of three ad-hoc routing protocols, namely AODV, DSDV and DSR. In contrast to earlier studies, the authors focused exclusively on the energy consumption and not on other metrics such as the number of routing packets. In particular, the authors studied the ‘range effects’ of the three protocols, i.e., how changes to the transmission power and transmission radius affected the overall energy consumed by routing-related packets. Due to the broadcast nature of the wireless medium, the energy spent in packet receptions was almost as important as the transmission power; using the number of transmissions as an indicator of the routing overhead could thus be fairly misleading. The studies showed that the energy overhead of the three protocols varied with the transmission power in distinct and non-obvious ways.

- **On the performance of a new 802.11-based low latency power control MAC protocol for ad-hoc networks** [230]
  Alizadeh-Shabdiz and Subramaniam proposed a new IEEE 802.11-based MAC protocol for ad hoc networks. The protocol incorporated multiple transmit power options in the
MAC layer by letting stations adaptively select the transmit power, and thus varied the coverage area. It was shown that the protocol was capable of improving network latency, which was a fundamental QoS measure. The latency reduction factor was more than two under low and moderate load conditions, and close to one at high offered loads, when compared to the standard IEEE 802.11 DCF MAC protocol. This reduction in latency was achieved with almost no decrease in network throughput.

- Power efficient range assignment in ad-hoc wireless networks [231]
  Althaus et al. studied the problem of assigning transmission ranges to the nodes of ad hoc wireless networks to minimize power consumption while ensuring network connectivity. The authors gave an exact branch and cut algorithm based on a new integer linear program formulation solving instances with up to 35-40 nodes in 1 hour; a proof that min-power symmetric connectivity with asymmetric power requirements is inapproximable within factor \((1 - \epsilon) \ln |V|\) for any \(\epsilon > 0\) unless \(P = NP\); an improved analysis for two approximation algorithms recently proposed by Calinescu et al. (TCS’02), decreasing the best known approximation factor to \(5/3 + \epsilon\); and a comprehensive experimental study comparing new and previously proposed heuristics with the above exact and approximation algorithms.

- Q-GSL: a framework for energy-conserving wireless multi-hop ad hoc networks [232]
  Safwat et al. proposed a novel framework, namely Quasi-Guaranteed System Lifetime (Q-GSL), which allowed the admission of flows without jeopardizing the limited energy of the wireless stations. A noteworthy feature of Q-GSL was that it provided a means for contention mitigation and load balancing. The upper bound on the packet rate was computed in the absence of the energy overheads associated with routing, contention resolution, channel sensing, etc. Hence, the upper bounds derived herein always constituted valid upper bounds on the amount of data transmitted by a source node per unit time. Likewise, the authors studied the main characteristics of the proposed techniques. The experiments revealed that load balancing was achieved amongst the routes and the nodes in the wireless ad hoc network without violating any of the energy constraints, and while adhering to a pre-computed deterministic minimum system lifetime.

- Energy concerns in wireless networks [233]
  Ephremides provided a brief overview of what constituted the major energy efficiency issues in ad hoc networks. Emphasis was placed on key conceptual points, which were then illustrated in the case study of wireless multicasting of connection-oriented traffic.

- Design challenges for energy-constrained ad hoc wireless networks [234]
  Goldsmith and Wicker gave a brief overview of ad hoc wireless networks and their applications with a particular emphasis on energy constraints. The authors then discussed
advances in the link, multiple access, network, and application protocols for these networks. The authors showed that cross-layer design of these protocols was imperative to meet emerging application requirements, particularly when energy was a limited resource.

- Energy-aware wireless networking with directional antennas: the case of session-based broadcasting and multicasting [235]
  Wieselthier et al. considered ad hoc wireless networks that used directional antennas and had limited energy resources. To explore quantitatively the advantage offered by the use of directional antennas over the case of omnidirectional antennas, the authors considered the case of connection-oriented multicast traffic. Building upon our prior work on multicasting algorithms, the authors introduced two protocols that exploited the use of directional antennas and evaluated their performance. The authors observed significant improvement with respect to the omnidirectional case, in terms of both energy efficiency and network lifetime. Additionally, the authors showed that further substantial increase in the network’s lifetime could be achieved by incorporating a simple measure of a node’s residual energy into the node’s cost function.

- Routing algorithm for specialised long-lifetime pico-radio networks [236]
  Wang and Arslan presented a novel routing algorithm which distributed the power consumption rate of each node evenly in a class of specialised mobile ad hoc networks, termed pico-networks. The algorithm added one additional factor to the cost metric of paths in order to prevent the overuse of specific piconodes. Simulation results showed that the new routing algorithm could prolong the lifetime and significantly improve the quality of a pico-radio network.

- DESP: a distributed economics-based subcontracting protocol for computation distribution in power-aware mobile ad hoc networks [237]
  Shang et al. presented a new economics-based power-aware protocol, called the distributed economic subcontracting protocol (DESP), that dynamically distributed task computation among mobile devices in an ad hoc wireless network. Mobile computation devices might be energy buyers, contractors, or subcontractors. Tasks were transferred between devices via distributed bargaining and transactions. When additional energy was required, buyers and contractors negotiated energy prices within their local markets. Contractors and subcontractors spent communication and computation energy to relay or execute buyers’ tasks. Buyers paid the negotiated price for this energy. Decision-making algorithms were proposed for buyers, contractors, and subcontractors, each of which had a different optimization goal. The authors built a wireless network simulator, called ESIM, to assist in the design and analysis of these algorithms. When the average communication energy required to transfer a task was less than the average energy required to execute a
task, the experimental results indicated that markets based on this protocol and decision-making algorithms fairly and effectively allocated energy resources among different tasks in both cooperative and competitive scenarios.

- **Energy-efficient DSPs for wireless sensor networks** [238]
  Wang and Chandrakasan studied system partitioning of computation to improve the energy efficiency of a wireless sensor networking application. The authors explored system partitioning between the sensor cluster and the base station, employing computation-communication tradeoffs to reduce energy dissipation. Also the authors showed that system partitioning of computation within the cluster could also improve the energy efficiency by using dynamic voltage scaling (DVS)

- **S-REMiT: a distributed algorithm for source-based energy efficient multicasting in wireless ad hoc networks** [239]
  Wang and Gupta proposed a distributed algorithm called S-REMiT for building an energy-efficient multicast tree in a wireless ad hoc network (WANET). S-REMiT employed a more realistic energy consumption model for wireless communication, which took into account the energy losses not only due to radio propagation but also the energy losses in the transceiver electronics. This enables S-REMiT to adapt a given multicast tree for a wide variety of wireless networks irrespective of whether they used long-range radios or short-range radios. The simulations showed that it performed better than BIP/MIP and EWMA algorithms.

- **Combining space-time coding with power-efficient medium access control for mobile ad-hoc networks** [240]
  Farha and Adve investigated the impact of space-time coding on an IEEE 802.11a based power-efficient Medium Access Control (MAC) protocol in a mobile ad hoc network (MANET). The new MAC protocol, MAC-2, preserved energy by sending information at the minimum power needed to reach the destination with a specified Packet Error Rate (PER). The analysis of space-time coding was conducted in practical environments, including spatial correlations between the fades connecting the transmitter and receiver antenna elements. Combining improvements in the physical layer with the new MAC-2 protocol led to tremendous savings in power and increase in overall network throughput, while maintaining a basic quality of service.

- **ECPS and E2la: new paradigms for energy efficiency in wireless ad hoc and sensor networks** [241]
  Safwat *et al.* proposed two schemes the objective of which was to enhance the operation of existing power-based multi-path routing protocols via cross-layer designs and optimal load assignments. The proposed schemes, namely, energy-efficient Load Assignment
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(E2LA), employed probabilistic dynamic programming techniques and utilized cross-layer interactions between the network and MAC layers. This might be the first time that MAC-originated information was used as the basis for achieving energy-efficient routing.

- A topology control algorithm for constructing power efficient wireless ad hoc networks [242]
  Wang et al. presented a localized algorithm for constructing power efficient topology for wireless ad hoc networks. Each mobile node determined its own transmission power based only on local information. The proposed algorithm first constructed the constrained Gabriel graph from the given unit disk graph and then reduced the total transmission power by allowing each node individually excises some replaceable links. The constructed topology was sparse, had a constant bounded power stretch factor, and the total transmission power was lower than those obtained from other proposed algorithms. In addition, compared with others, the algorithm requires lower time complexity to generate a solution, and could thus further save the energy for each mobile node. The authors demonstrated the performance improvements of the algorithm through simulations.

- Minimum energy-cost broadcast routing in ad hoc wireless networks [243]
  Li et al. discussed energy efficient broadcast in ad hoc wireless networks. The problem of concern was: given an ad hoc wireless network, to find a broadcast tree such that the energy cost of the broadcast tree was minimized. Each node in the network was assumed to have a fixed level of transmission power. The authors first proved that the problem was NP-hard, and proposed three heuristic algorithms, namely shortest path tree heuristic, greedy heuristic and node weighted Steiner tree based heuristic. The approximation ratio of the set-cover based heuristic was proved to be $(1 + 2 \ln(n - 1))$. Extensive simulations were conducted and the results demonstrated the efficiency of the proposed algorithms.

- Power optimization in fault-tolerant topology control algorithms for wireless multi-hop networks [244]
  In ad hoc wireless networks, it is crucial to minimize power consumption while maintaining key network properties. Hajiaghayi et al. studied power assignments of wireless devices that minimized power while maintaining k-fault tolerance. Specifically, the authors required all links established by this power setting be symmetric and formed a k-vertex connected subgraph of the network graph. The authors showed current heuristic approaches could use arbitrarily more power than the optimal solution. Hence, the authors sought approximation algorithms for this problem. The authors presented three approximation algorithms. The first algorithm gave an $O(k\alpha)$ approximation where $\alpha$ was the best approximation factor for the related problem in wired networks (the best $\alpha$ so far was in $O(\log k)$). Then, using a more complicated algorithm and careful analysis, the authors
achieved $O(k)$ approximation for general graphs. The authors then presented simple and practical distributed approximation algorithms for the cases of 2- and 3-connectivity in geometric graphs. In addition, the authors demonstrated how they could generalize this algorithm for k-connectivity in geometric graphs. Finally, the authors showed that these approximation algorithms compared favorably with existing heuristics. All algorithms presented could be used to minimize power while maintaining k-edge connectivity with guaranteed approximation factors.

- Energy consumption behavior and performance of directional virtual carrier sensing schemes [245]
  Energy drainage from a node is mainly caused by the power consumption of the nodes communication device. A MAC protocol is the main mechanism to provide efficient access to the shared wireless channel. Directional antennas provide several benefits over several omnidirectional ones including the reduced energy consumption in frame transmissions. Srisathapornphat and Shen studied and compared different generic directional virtual carrier sensing schemes (i.e., directional-RTS/CTS) in terms of their energy efficiency and performance. Both analytical and simulation results showed that the schemes using directional-RTS and/or directional-CTS were more energy efficient than other schemes.

- Regenerator versus simple-relay with optimum transmit power control for error propagation [246]
  Sahinoglu and Orlik studied power dissipation in relay-assisted wireless transmissions. Two types of assistance were considered: simple relaying and regenerative repeater. The authors found minimum transmit power levels to provision the same bit error rate in both cases. The simple-relay case considered power adjustment for error propagation at the intermediate relay node. Power consumption comparisons were made and results were discussed.

- Distributed power control for energy efficient routing in ad hoc networks [247]
  Bergamo et al. proposed distributed power control as a means to improve the energy efficiency of routing algorithms in ad hoc networks. Each node in the network estimated the power necessary to reach its own neighbors, and this power estimate was used both for tuning the transmit power (thereby reducing interference and energy consumption) and as the link cost for minimum energy routing. With reference to classic routing algorithms, such as Dijkstra and Link State, as well as more recently proposed ad hoc routing schemes, such as AODV, the authors demonstrated by extensive simulations that in many cases of interest our scheme provided substantial transmit energy savings while introducing limited degradation in terms of throughput and delay.

- Routing mechanisms for mobile ad hoc networks based on the energy drain rate [248]
Kim et al. proposed a new metric, the drain rate, to forecast the lifetime of nodes according to current traffic conditions. This metric was combined with the value of the remaining battery capacity to determine which nodes could be part of an active route. The authors described new route selection mechanisms for MANET routing protocols, called the minimum drain rate (MDR) and the conditional minimum drain rate (CMDR). MDR extended nodal battery life and the duration of paths, while CMDR also minimized the total transmission energy consumed per packet. Using the ns-2 simulator and the dynamic source routing (DSR) protocol, the authors compared MDR and CMDR against prior proposals for energy-aware routing and showed that using the drain rate for energy-aware route selection offered superior performance results.

- Growth of wireless ad hoc networks [249]
  The utility of a node in an energy-limited wireless ad hoc network is defined as a positive linear function of the number of bits that the node sends as a source and the number of bits that it receives as a destination. First, Rodoplu and Meng showed that under the one-to-one traffic model in which every node wanted to send traffic to a randomly chosen destination node, a utility that grew asymptotically at least as $c_n(N/\log N)^{(n-1)/2}$ was achievable for every node when the nodes were distributed randomly on the surface of a fixed sphere. In this expression, $N$ denoted the number of nodes, $n$ denoted the transmit power fall-off exponent, and $c_n$ was a constant that depended on $n$ and was independent of $N$. Second, the authors introduced a "dollars-per-Joule pricing" system for wireless ad hoc networks, in which each node could charge any other node a price per Joule of energy that it expended on the other node’s traffic. Under this pricing system, the authors extended the definition of the utility of a node to include the revenue that the node raised and the payments that it made on the network. The authors showed that the core capacity region of a wireless ad hoc network was non-empty under this dollars-per-Joule pricing system. Further, the authors showed that there existed a sequence of utility vectors in the core capacity region such that the average of the utilities of the nodes grew asymptotically at least as $c_n(N/\log N)^{(n-1)/2}$ under the one-to-one traffic model.

- Energy efficient routing protocols for mobile ad hoc networks [250]
  Although establishing correct and efficient routes is an important design issue in mobile ad hoc networks (MANETs), a more challenging goal is to provide energy efficient routes because mobile nodes’ operation time is the most critical limiting factor. Yu et al. surveyed and classified the energy-aware routing protocols proposed for MANETs. They minimized either the active communication energy required to transmit or receive packets or the inactive energy consumed when a mobile node stayed idle but listened to the wireless medium for any possible communication requests from other nodes. Transmission power control approach and load distribution approach belonged to the former
category, and sleep/power-down mode approach belonged to the latter category. While it was not clear whether any particular algorithm or a class of algorithms was the best for all scenarios, each protocol had definite advantages/disadvantages and was well suited for certain situations. The purpose of this paper was to facilitate the research efforts in combining the existing solutions to offer a more energy efficient routing mechanism.

- Power-aware broadcasting and activity scheduling in ad hoc wireless networks using connected dominating sets [251]
  In ad hoc mobile wireless networks, owing to host mobility, broadcasting is expected to be more frequently used to find a route to a particular host, to page a host, and to alarm all hosts. A straightforward broadcasting by flooding is usually very costly and will result in substantial redundancy and more energy consumption. Power consumption is an important issue since most mobile hosts operate on battery. Broadcasting based on a connected dominating set is a promising approach, where only nodes in the dominating set need to relay the broadcast packet. A set is dominating if all the nodes in the system are either in the set or are neighbors of nodes in the set. Wu and Li proposed a simple and efficient distributed algorithm for calculating connected dominating set in ad hoc wireless networks, where connections of nodes are determined by their geographical distances. In general, nodes in the connected dominating set consume more energy to handle various bypass traffic than nodes outside the set. To prolong the life span of each node and, hence, the network by balancing the energy consumption in the system, nodes should be alternately chosen to form a connected dominating set. Activity scheduling deals with the way of rotating the role of each node among a set of given operation modes (e.g. dominating nodes versus dominated nodes). Wu et al. proposed to apply the notion of power-aware connected dominating set to broadcasting and activity scheduling. The effectiveness of the proposed method in prolonging the life span of the network was confirmed through simulation.

- Three power-aware routing algorithms for sensor networks [252]
  Aslam et al. discussed online power-aware routing in large wireless ad hoc networks (especially sensor networks) for applications in which the message sequence was not known. The authors sought to optimize the lifetime of the network. The authors showed that online power-aware routing did not have a constant competitive ratio to the off-line optimal algorithm. The authors developed an approximation algorithm called $\max - \min zP_{\min}$ that had a good empirical competitive ratio. To ensure scalability, the authors introduced a second online algorithm for power-aware routing. This hierarchical algorithm was called zone-based routing. The experiments showed that its performance was quite good. Finally, the authors described a distributed version of this algorithm that did not depend on any centralization.
A node scheduling scheme for energy conservation in large wireless sensor networks [253]

In wireless sensor networks that consist of a large number of low-power, short-lived, unreliable sensors, one of the main design challenges is to obtain long system lifetime without sacrificing system original performances (sensing coverage and sensing reliability). Tian and Georganas proposed a node-scheduling scheme, which could reduce system overall energy consumption, therefore increasing system lifetime, by identifying redundant nodes in respect of sensing coverage and then assigning them an off-duty operation mode that had lower energy consumption than the normal on-duty one. The scheme aimed to completely preserve original sensing coverage theoretically. Practically, sensing coverage degradation caused by location error, packet loss and node failure was very limited, not more than 1% as shown by the experimental results. In addition, the experimental results illustrated that certain redundancy was still guaranteed after node-scheduling, which the authors believed could provide enough sensing reliability in many applications. The authors implemented the proposed scheme in NS-2 as an extension of the LEACH protocol and compared its energy consumption with the original LEACH. Simulation results exhibited noticeably longer system lifetime after introducing the scheme than before.
Chapter 18

Directional Antenna

- Improving system performance of ad hoc wireless network with directional antenna [254]
  It has been shown that use of directional antenna in the context of ad hoc wireless networks can largely reduce radio interference, thereby improving the utilization of wireless medium. However, that alone does not always guarantee improvement in overall system performance. Bandyopadhyay et al. identified several criteria and investigated their interrelationships and impact on overall system performance in this context. The methodology used optimization techniques using multicriteria decision analysis. The authors use analytic hierarchy process (AHP) to identify relative weights of different criteria under different application-specific scenario in order to solve the optimization problem for each scenario by TOPSIS approach. The result showed that the parameter setting required to get optimum performance was application-specific; depending on the situation or application-scenario, several parameters needed to be controlled to get better system performance.

- Smart antenna system analysis, integration and performance for mobile ad-hoc networks (MANETs) [255]
  Bellofiore et al. focused on the interaction and integration of several critical components of a mobile ad-hoc network (MANET) using smart antenna systems. A MANET was a wireless network where the communicating nodes were mobile and the network topology was continuously changing. One of the central motivations for this work came from the observed dependence of the overall network throughput on the design of the adaptive antenna system and its underlying signal processing algorithms. In fact, a major objective of this work was to study and document the overall efficiency of the network in terms of the antenna pattern and the length of the training sequence used by the beamforming algorithms. This study also considered in sufficient detail problems dealing with the choice of direction of arrival algorithm and the performance of the adaptive beamformer.
in the presence of antenna coupling effects. Furthermore, the authors presented strategies and algorithms to combat the effects of fading channels on the overall system.

- Great Expectations: The Value of Spatial Diversity in Wireless Networks [256]  
  Diggavi et al. examined the effect of spatial diversity on the throughput and reliability of wireless networks. Spatial diversity was realized through multiple independently fading transmit/receive antenna paths in single-user communication and through independently fading links in multiuser communication. Adopting spatial diversity as a central theme, the authors start by studying its information-theoretic foundations, then the authors illustrated its benefits across the physical (signal transmission/coding and receiver signal processing) and networking (resource allocation, routing, and applications) layers. Throughout the paper, the authors discussed engineering intuition and tradeoffs, emphasizing the strong interactions between the various network functionalities.
Chapter 19

Location-Aware

- **DL-GRID**: A QoS routing protocol for ad hoc networks [257]
  Liu and Li investigated the QoS routing problem in Ad Hoc networks. The authors proposed a location aware routing protocol with QoS provision. The proposed scheme, named DL-GRID, considered a Dual-layered-grid system configuration to reduce each mobile’s transmission power so as to enhance the bandwidth utilization. Simulation results showed that DL-GRID established a stable QoS guaranteed route meanwhile saves bandwidth.

- **Multi-step increase of the forwarding zone for LAR protocol in ad hoc networks** [258]
  De rango et al. focused on that class of routing algorithms using information about geographical location of the mobile nodes in wireless ad hoc networks. The authors proposed a modification in the way of re-computing the forwarding zone of route request packets for the location-aided routing (LAR) protocol. The shape and extension of this zone influenced the protocol performance in terms of control overhead, packet delay and loss. The authors studied the impact of a multi-step resizing of the request zone on the LAR protocol performance, and made comparisons with other routing protocols (such as the original LAR scheme 1 and the promiscuous-dynamic source routing protocol). Simulation results showed how their approach added to the advantages of LAR scheme 1 the further advantage of reducing the control overhead.

- **LAKER**: location aided knowledge extraction routing for mobile ad hoc networks [259]
  Li and Mohapatra presented a location aided knowledge extraction routing (LAKER) protocol for MANETs, which utilized a combination of caching strategy in dynamic source routing (DSR) and limited flooding area in location aided routing (LAR) protocol. The key novelty of LAKER was that it could gradually discover knowledge of topological characteristics such as population density distribution of the network. This knowledge could be organized in the form of a set of guiding routes, which included a chain of important
positions between a pair of source and destination locations. The guiding route information was learned during the route discovery phase, and it could be used to guide future route discovery process in a more efficient manner. LAKER was especially suitable for mobility models where nodes were not uniformly distributed. LAKER could exploit the topological characteristics in these models and limit the search space in route discovery process in a more refined granularity. Simulation results showed that LAKER outperformed LAR and DSR in term of routing overhead, saving up to 30% broadcast routing message compared to the LAR approach.

• ELF: Efficient Location Forwarding in Ad hoc Networks [260]
  Recently, a new family of protocols has been introduced for large scale ad hoc networks that makes use of the approximate location of nodes in the network for geography based routing. Location management plays an important role in such protocols, and previous work in this area has shown that the asymptotic overhead of location management is heavily dependent on the service primitives (location registration, maintenance and discovery) supported by a location management protocol. Currently, SLALoM, which is a grid-based protocol optimized for large node movements, achieves the best known upper bound on the asymptotic worst case overhead of location management. However, the location registration cost in SLALoM dominates other costs for all practical purposes, and thus novel schemes need to be designed to limit this control traffic. Philip and Qiao use the idea of location forwarding to devise a new scheme called ELF that limited the signalling traffic, and thus enhanced the scalability of location management in large ad hoc networks. The authors found that, while the asymptotic overhead cost by such an improvisation matches that of SLALoM, ELF outperforms SLALoM in average case scenarios.

• Geographic routing without location information [261]
  For many years, scalable routing for wireless communication systems was a compelling but elusive goal. Recently, several routing algorithms that exploit geographic information (e.g. GPSR) have been proposed to achieve this goal. These algorithms refer to nodes by their location, not address, and use those coordinates to route greedily, when possible, towards the destination. However, there are many situations where location information is not available at the nodes, and so geographic methods cannot be used. Rao et al. defined a scalable coordinate-based routing algorithm that did not rely on location information, and thus could be used in a wide variety of ad hoc and sensornet environments.

• Energy and latency performance of geographic random forwarding for ad hoc and sensor networks [262]
  Zorzi and Rao described a novel forwarding technique based on geographical location of the nodes involved and random selection of the relaying node via contention among
receivers. A collision avoidance scheme based on this idea was described in detail, and an approximate analysis was provided. The proposed scheme was compared with STEM, and was shown to perform significantly better for sufficient node density.

- Location Information-Aided Task-Oriented Self-Organization of Ad-Hoc Sensor Systems [263]

Premaratne et al. proposed a novel task-oriented self-organization algorithm that accounted for mostly location-dependent tasks and heterogeneous sensors inherent in dense ad-hoc sensor systems. It formed a sensor group for an announced task by sequentially selecting the best matched sensors using a leader election algorithm and a residual task calculation algorithm. To improve the associated communication overhead, the sensor node location information was used in task broadcasting, thus confining the algorithm implementation to a dynamically maintained contributor group which comprised of those sensors which might contribute to the task. Sensor localization was based on a refinement of an algorithm which utilized only the neighborhood information of each sensor node corresponding to its each preset radio transmission power level. The proposed self-organization algorithm and how various system parameters affected its performance were examined via extensive simulations. In a densely deployed sensor system, when the refined localization scheme was demonstrated to achieve very good localization, the proposed self-organization algorithm consistently yielded a sensor group that covers the announced task.

- Cramer-Rao Bound Analysis of Distributed Positioning in Sensor Networks [264]

In future applications of sensor networking technology, it is envisioned that nodes will be able to determine their geographical position by measuring the range differences between one another in a collaborative fashion. Larsson aimed to provide quantitative expressions that could be used both to facilitate an understanding for why such distributed positioning worked and to assess the ultimately achievable accuracy in practice. Specifically, the author computed the Cramer-Rao bound on the positioning accuracy, under different assumptions on the network synchronization. Numerical examples illustrated the results.
Chapter 20

Mobility

• Dead reckoning in mobile ad hoc networks [265]
  Agarwal and Das proposed a predictive model-based mobility tracking method, called dead reckoning, for mobile ad hoc networks. It disseminated both location and movement models of mobile nodes in the network so that every node was able to predict or track the movement of every other node with a very low overhead. This technique was applied to solve the unicast routing problem by modeling link costs using both link lifetime and geographic distance from the destination to the link egress point. This method presented a much superior routing performance compared to either DSR or AODV, two other popular routing protocols, particularly in terms of delivery fraction and routing load.

• A mobility tracking model for wireless ad hoc networks [266]
  Zaidi and Mark proposed a novel scheme for tracking the mobility of users in a wireless ad hoc network. Mobile nodes tracked their positions using pilot signal strengths from neighboring nodes within a local coordinate system based on relative distances between nodes. Node mobility was modeled as a linear system driven by a discrete command semi-Markov process. Mobility tracking was performed using an extended Kalman filter preceded by an averaging filter. The numerical results showed that the mobility tracking scheme performs effectively and could be used to enhance routing performance in ad hoc networks.

• A comparative study of mobility prediction in fixed wireless networks and mobile ad hoc networks [267]
  Chellapa et al. introduced a mobility prediction scheme that proposed the use of a new sector-based tracking of mobile users, with a sector-numbering scheme to predict user movements. The proposed scheme was applicable for both the fixed network and the ad hoc networking structures. The study showed that accurate prediction was possible with reduced area of tracking for both types of networks.
Mobility-enhanced positioning in ad hoc networks [268]
Lim and Rao discussed and investigated the effects of mobility on positioning of wireless ad hoc networks. The authors presented a mobility-enhanced ad hoc positioning (MAP) scheme, where the authors leveraged on the mobility of nodes within network. The scheme used the hop counts information from fixed reference nodes to perform positioning and improves accuracy by using mobile nodes to "bridge" gaps within neighborhoods where accurate information was not available. Simulation showed that using mobility did improve the performance of such "hop count"-based positioning schemes.

The node distribution of the random waypoint mobility model for wireless ad hoc networks [269]
Bettstetter et al. presented a detailed analytical study of the spatial node distribution generated by random waypoint mobility. More specifically, the authors considered a generalization of the model in which the pause time of the mobile nodes was chosen arbitrarily in each waypoint and a fraction of nodes might remain static for the entire simulation time. The authors showed that the structure of the resulting distribution was the weighted sum of three independent components: the static, pause, and mobility component. This division enabled us to understand how the model’s parameters influenced the distribution. The authors derived an exact equation of the asymptotically stationary distribution for movement on a line segment and an accurate approximation for a square area. The good quality of this approximation was validated through simulations using various settings of the mobility parameters. In summary, this article gave a fundamental understanding of the behavior of the random waypoint model.

Towards realistic mobility models for mobile ad hoc networks [270]
One of the most important methods for evaluating the characteristics of ad hoc networking protocols is through the use of simulation. Simulation provides researchers with a number of significant benefits, including repeatable scenarios, isolation of parameters, and exploration of a variety of metrics. The topology and movement of the nodes in the simulation are key factors in the performance of the network protocol under study. Once the nodes have been initially distributed, the mobility model dictates the movement of the nodes within the network. Because the mobility of the nodes directly impacts the performance of the protocols, simulation results obtained with unrealistic movement models may not correctly reflect the true performance of the protocols. The majority of existing mobility models for ad hoc networks do not provide realistic movement scenarios; they are limited to random walk models without any obstacles. Jardosh et al. proposed to create more realistic movement models through the incorporation of obstacles. These obstacles were utilized to both restrict node movement as well as wireless transmissions. In addition to the inclusion of obstacles, the authors constructed movement paths using the
Voronoi diagram of obstacle vertices. Nodes could then be randomly distributed across the paths, and could use shortest path route computations to destinations at randomly chosen obstacles. Simulation results showed that the use of obstacles and pathways had a significant impact on the performance of ad hoc network protocols.

- A mobility measure for mobile ad hoc networks [271]
  Kwak et al. proposed a mobility measure for mobile ad hoc networks that was flexible because one could customize the definition of mobility using a remoteness function. The proposed measure was consistent because it had a linear relationship to the rate at which links were established or broken for a wide range of mobility scenarios, where a scenario consisted of the choice of mobility model, the physical dimensions of the network, the number of nodes. This consistency was the strength of the proposed mobility measure because the mobility measure reliably represented the link change rate regardless of network scenarios.

- A survey of mobility models for ad hoc network research [272]
  In the performance evaluation of a protocol for an ad hoc network, the protocol should be tested under realistic conditions including, but not limited to, a sensible transmission range, limited buffer space for the storage of messages, representative data traffic models and realistic movements of the mobile users (i.e. a mobility model). Camp et al. surveyed mobility models that were used in the simulations of ad hoc networks. The authors described several mobility models that represented mobile nodes whose movements were independent of each other (i.e. entity mobility models) and several mobility models that represented mobile nodes whose movements were dependent on each other (i.e. group mobility models). The goal of this paper was to present a number of mobility models in order to offer researchers more informed choices when they were deciding on a mobility model to use in their performance evaluations. Lastly, the authors presented simulation results that illustrated the importance of choosing a mobility model in the simulation of an ad hoc network protocol. Specifically, the authors illustrated how the performance results of an ad hoc network protocol drastically changed as a result of changing the mobility model simulated.
Chapter 21

Clustering

- An analysis of mobile radio ad hoc networks using clustered architectures [273]
  Skold et al. presented a novel approach for evaluating the routing efficiency of clustered architectures, as compared to flat ones in mobile scenarios. The results showed that the clustered architecture needed to be very carefully designed in order to be more efficient than a flat architecture for small to medium sized networks of up to 400 nodes. That is, a clusterhead needed to have good knowledge of the links in its cluster such a good route through the cluster could be selected.

- Efficient clustering-based routing protocol in mobile ad-hoc networks [274]
  Ahn et al. proposed a new routing protocol for mobile ad-hoc networks. It was a kind of hybrid routing protocol (HRP). It lies somewhere between proactive and reactive routing protocols (PRP and RRP). The proposed routing protocol worked on the basis of a virtual cluster, consisting of a collection of those nodes that were only one-hop distance away. The idea was to reduce significantly control overheads, such as route query packets, as well as the flooding time for collecting the network topology information at a destination. The key feature of the proposed scheme was that it drew on the short packet transfer delay of PRP and the small control overhead performance of RRP. A backup route was intended to improve the delay performance further. A disconnected route could be replaced by a backup route, if available. Computing the backup route did not increase computational overheads. Computer simulation studies demonstrated the superior performance of the proposed scheme. In particular, it was not sensitive to changing network topology, had shorter transfer delay, reasonable control overheads and appreciable throughput. It exhibited all these desirable characteristics without compromising on other important performance measures.

- Capacity compatible 2-level link state routing for ad hoc networks with mobile clusterheads [275]
The throughput of a mobile ad hoc network (MANET) is determined by the transceiver link capacity available at each node and the type of traffic pattern that is prevalent in the network. In order for a routing protocol to be scalable, its control overhead must not exceed transceiver link capacity. To achieve capacity compatible routing, hierarchical techniques may be employed. Supec and Marsic described how link state routing, with a single layer of hierarchy, provided sufficient scalability for MANETs where the traffic pattern consisted of unicast communication between arbitrary pairs of nodes.

- Optimizing clustering algorithm in mobile ad hoc networks using simulated annealing [276]
  Turgut et al. demonstrated how simulated annealing algorithm could be applied to clustering algorithms used in ad hoc networks; specifically the weighted clustering algorithm (WCA) proposed before was optimized by simulated annealing. The proposed technique was such that each clusterhead handled the maximum possible number of mobile nodes in its cluster in order to facilitate the optimal operation of the MAC protocol. Consequently, it resulted in the minimum number of clusters and hence clusterheads. Simulation results exhibited improved performance of the optimized WCA than the original WCA.

- A distributed self-organization algorithm for ad-hoc sensor networks [277]
  Zhang et al. proposed a distributed task-oriented self-organization algorithm that enabled sensors in an ad-hoc network to organize them according to the task being announced. When a task was announced, a distributed leader election algorithm was used to select the sensor that best ‘matched’ the announced task based on minimizing a distance measure between the task and sensor specifications. The selected sensor then used a task decomposition method to generate and announce the residual tasks that ‘covered’ the matching error. In this manner, sensors were sequentially selected until all residual tasks were ‘covered’. All sensors selected by the algorithms from a sensor group for the originally announced task. To improve the communication overhead of a previous version of this algorithm, location information of each sensor was used to dynamically maintain a contributor group of sensors that might contribute to the announced task. Leader election and all task announcements were confined to this group.

- Channel access-based self-organized clustering in ad hoc networks [278]
  Cai et al. described a distributed clustering algorithm for multihop ad hoc networks. The authors first proposed a randomized control channel broadcast access method to maximize the worst-case control channel efficiency, based on which a distributed clustering algorithm was proposed. Both theoretical analysis and simulations indicated that the proposed clustering algorithm took much less time and overhead to cluster a given network with more stable cluster structure, while incurring very small maintenance overhead in a
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dynamic network resulting from the mobility of the mobile stations.

- Multi-level hierarchies for scalable ad hoc routing [279]
Belding-Royer presented two hierarchical clustering protocols that improve the scalability of ad hoc routing protocols. The Adaptive Routing using Clusters (ARC) protocol created a one-level clustered hierarchy across an ad hoc network, while the Adaptive Routing using Clustered Hierarchies (ARCH) protocol created a multi-level hierarchy which was able to dynamically adjust the depth of the hierarchy in response to the changing network topology. It was experimentally shown that these protocols, when coupled with an ad hoc routing protocol, produce throughput improvements of up to 80% over the ad hoc routing protocol alone.

- Time and message complexities of the generalized distributed mobility-adaptive clustering (GDMAC) algorithm in wireless multihop networks [280]
Bettstetter and Friedrich studied the convergence time and message complexity of Basagni’s generalized DMAC clustering algorithm. The results showed how many time steps and signaling messages were typically needed after a single topology change to re-achieve a stable and valid cluster structure. Furthermore, the authors discussed chain reactions that could occur along a path if certain conditions were fulfilled. Finally, the authors regarded a mobile scenario in order to analyze (a) the number of signaling messages per node and time step and (b) the percentage of time steps in which the cluster structure was invalid. The results gave a qualitative insight on the behavior of clustering in ad hoc networks. In particular, they showed that tuning the density of clusterheads and employing a hysteresis parameter for cluster changes could significantly improve the performance.

- Kinetic minimum-power routing and clustering in mobile ad-hoc networks [281]
Gentile et al. previously developed a distributed routing algorithm which minimizes the number of overhead messages necessary to maintain the minimum-power multi-hop routes in a mobile ad-hoc network, assuming a piecewise linear model for the motion of the nodes. The authors extended the routing algorithm to include clustering as well, to reduce further the number of overhead messages at the expense of sub-optimal routes. A single parameter controlled the degree of clustering, and consequently the degree of sub-optimality, rather than arbitrary parameters such as maximum cluster size or maximum distance between nodes. The proposed algorithm converged in a finite number of iterations to both stable routes and stable clusters, and by setting the cluster parameter to 0 collapses to the original routing algorithm with no clusters and optimum routes.

- CLTC: a cluster-based topology control framework for ad hoc networks [282]
The topology of an ad hoc network has a significant impact on its performance in that
a dense topology may induce high interference and low capacity, while a sparse topology is vulnerable to link failure and network partitioning. Topology control aims to maintain a topology that optimizes network performance while minimizing energy consumption. Existing topology control algorithms utilize either a purely centralized or a purely distributed approach. A centralized approach, although able to achieve strong connectivity ($k$-connectivity for $k \geq 2$), suffers from scalability problems. In contrast, a distributed approach, although scalable, lacks strong connectivity guarantees. Shen et al. proposed a hybrid topology control framework, Cluster-based Topology Control (CLTC), that achieved both scalability and strong connectivity. By varying the algorithms utilized in each of the three phases of the framework, a variety of optimization objectives and topological properties could be achieved. The authors presented the CLTC framework; described topology control algorithms based on CLTC and proved that $k$-connectivity was achieved using those algorithms; analyzed the message complexity of an implementation of CLTC, namely, CLTC-A, and presented simulation studies that evaluated the effectiveness of CLTC-A for a range of networks.

- Geometric spanners for wireless ad hoc networks [283]

Alzoubi et al. proposed a new geometric spanner for static wireless ad hoc networks, which could be constructed efficiently in a localized manner. It integrated the connected dominating set and the local Delaunay graph to form a backbone of the wireless network. Priori arts showed that both structures could be constructed locally with bounded communication costs. This new spanner had these following attractive properties: 1) the backbone was a planar graph, 2) the node degree of the backbone was bounded from above by a positive constant, 3) it was a spanner for both hops and length, 4) it could be constructed locally and was easy to maintain when the nodes move around, and 5) moreover, the communication cost of each node was bounded by a constant. Simulation results were also presented for studying its practical performance.
Chapter 22

Neighbour Discovery

• Control overhead reduction for neighbour knowledge acquisition in mobile ad hoc networks [284]
  Neighbour knowledge in mobile ad hoc networks provides important functionality for a number of protocols. Yoo et al. presented an approach where each node acquired neighbour knowledge by observing not only hello packets but also flooded packets. Analysis results showed that this method offered significant improvement over the original scheme.

• INK: implicit neighbor knowledge routing in ad hoc networks [285]
  Yoo et al. proposed the Implicit Neighbor Knowledge (INK) routing scheme, which aimed to reduce the flooding overhead by using the simple probability based method. INK routing scheme used a variable probability defined by its neighbor size. INK tried to acquire neighbor knowledge without the usage of any periodic hello packets by observing flooded packets. The proposed scheme kept up the reachability of blink flooding while maintaining the simplicity of probability based schemes.

• A simple neighbour discovery procedure for bluetooth ad hoc networks [286]
  Bluetooth was designed to replace cables between electronic devices, but it can also be used to build ad hoc networks. In the cable replacement scenario nodes can discover each other using the inquiry procedure. This has been designed to satisfy the requirements of cable replacement applications so that it discovers all neighbours in a fixed amount of time. On the other hand, the inquiry procedure is not well suited for nodes in a Bluetooth ad hoc network, where we found three main weaknesses. First, inquiry takes a lot of time and therefore it requires too much overhead if used regularly. Second, it is very inefficient to transmit data simultaneously with the inquiry. Third, the inquiry assumes asymmetric roles, which is not well suited to an ad hoc network of peer nodes. To resolve these problems, Ronai and Kail proposed the Simple Neighbour Discovery (SND) procedure. The authors evaluated it using analytical and simulation methods and
showed that it was configurable in the trade-off between discovery time and overhead. The results showed that the SND procedure was more efficient in an ad hoc network of peer Bluetooth nodes than the inquiry procedure.
Chapter 23

Network Model

• Lower bound on path availability in ad hoc network [287]
  Yu and Li proposed a general ad hoc network model and derives a statistic lower bound
  of link and path availability in ad hoc networks. Finally, simulation results of several
  commonly used mobility models were given to verify their theory.

• Supporting service differentiation for real-time and best-effort traffic in stateless wireless
  ad hoc networks (SWAN) [288]
  Ahn et al. proposed SWAN, a stateless network model which uses distributed control
  algorithms to deliver service differentiation in mobile wireless ad hoc networks in a sim-
  ple, scalable and robust manner. The proposed architecture was designed to handle both
  real-time UDP traffic, and best effort UDP and TCP traffic without the need for the intro-
  duction and management of per-flow state information in the network. SWAN supported
  per-hop and end-to-end control algorithms that primarily relied on the efficient operation
  of TC/IP protocols. In particular, SWAN used local rate control for best-effort traffic,
  and sender-based admission control for real-time UDP traffic. Explicit congestion notifi-
  cation (ECN) was used to dynamically regulate admitted real-time sessions in the face of
  network dynamics brought on by mobility or traffic overload conditions. SWAN did not
  require the support of a QoS-capable MAC to deliver service differentiation. Rather, real-
  time services were built using existing best effort wireless MAC technology. Simulation,
  analysis, and results from an experimental wireless testbed showed that real-time applica-
  tions experienced low and stable delays under various multihop, traffic, and mobility
  conditions.
Chapter 24

Hybrid and Hierarchical Networks

- Hybrid Wireless Network Protocols [289]
  Chang et al. proposed hybrid wireless network protocols to combine the advantages of BS-oriented and ad hoc wireless networks. They allowed two mobile hosts to communicate directly (one-hop direct transmission) or through another mobile host (two-hop direct transmission) within a BS-oriented network. The hybrid protocols were more flexible, reliable, and had better performance than the traditional protocols. Simulation results showed that two-hop direct-transmission had a lower non-completion probability. If the communicating parties were always within a two-hop direct-transmission area, the rate of complete communication improved by about 20%.

- Hybrid gateway advertisement scheme for connecting mobile ad hoc networks to the Internet [290]
  When a node in a mobile ad hoc network wants to send data packets to the Internet, and therefore outside of its local ad hoc network, it has to obtain information about the available Internet gateways: i.e. which one to use and how to get there. To accomplish this, nodes can utilize either a unsolicited gateway discovery mechanism or relay on unsolicited gateway advertisement packets sent by gateways. Lee et al. proposed two kinds of advertising schemes, which were based on the observation of traffic and mobility patterns, and were designed to avoid generating unnecessary packets in the MANET (Mobile Ad hoc Network), in addition to giving mobile nodes more opportunity to use the shortest path to the Internet.

- MEWLANA-mobile IP enriched wireless local area network architecture [291]
  The idea of extending mobile IP capabilities to ad hoc networks introduces fast agent discovery, increases cell coverage of access points, and extends ad hoc network size by providing connection to the Internet. Ergen and Puri proposed two protocols called MEWLANA-TD and MEWLANA-RD based on DSDV and a novel ad hoc routing called
tree based bidirectional routing (TBBR) respectively in addition to the proposed protocols based on on-demand routing. The authors classified the ad hoc environment into regions and presented which protocol was appropriate for which region.

- Ad hoc routing for cellular coverage extension [292]
  Gruber et al. proposed a novel ad hoc routing for cellular coverage extension (ARCE) algorithm. The utilization of ad hoc network nodes as relays for calls designated to the base station greatly improves the flexibility of cellular networks. It reduced the CDMA inherent cell breathing behavior by reducing the maximum necessary cell radius. Furthermore, it increased the distance between adjacent base stations and therewith the cost of deployment.

- Multihop sensor network design for wide-band communications [293]
  Gharavi and Ban presented a master/slave cellular-based mobile ad hoc network architecture for multihop multimedia communications. The proposed network was based on a new paradigm for solving the problem of cluster-based ad hoc routing when utilizing existing wireless local area network (WLAN) technologies. The network architecture was a mixture of two different types of networks: infrastructure (master-and-slave) and ad hoc. In this architecture, the participating slave nodes (SNs) in each cluster communicated with each other via their respective master nodes (MNs) in an infrastructure network. In contrast to traditional cellular networks where the base stations are fixed (e.g., interconnected via a wired backbone), in this network the MNs (e.g., base stations) were mobile; thus, interconnection was accomplished dynamically and in an ad hoc manner.

- Mixed-mode WLAN: the integration of ad hoc mode with wireless LAN infrastructure [294]
  In the traditional IEEE 802.11 wireless LAN using infrastructure mode, all users share the same channel and all packets are forwarded by an access point (AP). As a result, as the number of users in the cell increases, the throughput for each user degrades substantially. If there are users communicating with each other within the cell (as in conferencing or file exchange applications), such throughput degradation could be relieved by making these users communicate through ad hoc connections without going through the AP. The advantages are multi-fold. First, the traffic load at the AP is reduced, hence relieving the contention. Second, ad hoc connections are single-hop, hence improving the channel efficiency. Moreover, ad hoc connections could use different channels, hence multiplying the system bandwidth. Chen et al. proposed to integrate the infrastructure mode and the ad hoc mode in a wireless network so as to achieve these advantages. The authors presented a framework for such mixed-mode wireless LAN (termed M2-WLAN). In such a network, a node could dynamically switch between the infrastructure mode and the ad
hoc mode according to the instruction of the AP, and hence the switching was transparent to the users. Using simulations, the authors showed that M2-WLAN could indeed improve system throughput substantially without user’s manual configuration.

- **UCAN**: a unified cellular and ad-hoc network architecture [295]
  Luo et al. proposed the Unified Cellular and Ad-Hoc Network (UCAN) architecture for enhancing cell throughput, while maintaining fairness. In UCAN, a mobile client had both 3G cellular link and IEEE 802.11-based peer-to-peer links. The 3G base station forwarded packets for destination clients with poor channel quality to proxy clients with better channel quality. The proxy clients then used an ad-hoc network composed of other mobile clients and IEEE 802.11 wireless links to forward the packets to the appropriate destinations, thereby improving cell throughput. The authors refined the 3G base station scheduling algorithm so that the throughput gains of active clients were distributed proportional to their average channel rate, thereby maintaining fairness. With the UCAN architecture in place, the authors proposed novel greedy and on-demand protocols for proxy discovery and ad-hoc routing that explicitly leveraged the existence of the 3G infrastructure to reduce complexity and improved reliability. The authors further proposed a secure crediting mechanism to motivate users to participate in relaying packets for others. Through extensive simulations with HDR and IEEE 802.11b, the authors showed that the UCAN architecture could improve individual user’s throughput by up to 310% and the aggregate throughput of the HDR downlink by up to 60%.

- **Mobile communication systems with multi-layered wireless network using ad hoc network** [296]
  Wireless ad hoc networks have been studied from several viewpoints. However, the studies have not focused on the relationship between ad hoc networks and other wireless networks or the characteristics of combined networks. Ogose et al. described a mobile radio communication system with multi-layered wireless network that used ad hoc networks. The major purposes of the proposed system were to obtain anti-shadow fading characteristics and to disperse the traffic in a service area. First, the multi-layered wireless network architecture was described. Then, the spectrum efficiency was given while taking into account the number of hoppings among the ad hoc networks. Finally, as an example of the multi-layered wireless network system, a positioning system with ten times higher accuracy than a conventional PHS (Personal Handy phone System) based system was introduced.

- **Self-organizing packet radio ad hoc networks with overlay (SOPRANO)** [297]
  The SOPRANO project involves a novel adaptive and scalable wireless network architecture utilizing a mixture of cellular and multihop packet radio system topologies with the
potential to support a variety of applications including high-data rate Internet and multimedia traffic at a reasonable degree of implementation complexity. Zadeh et al. discussed the potential benefits of this structure and addressed several relevant issues necessary to support such a network. More specifically, it focused on connection establishment and self-organization, investigated the formulation of an optimum transmission strategy, and examined some of the techniques by which the capacity or enhance the system performance in this multihop network could be augmented. The authors also presented capacity bounds that illustrated how these techniques helped in trading off conserved power for a multifold capacity advantage.

- Master-slave cluster-based multihop ad-hoc networking [298]

Gharavi and Ban presented a master-slave cluster-based mobile ad-hoc network architecture for multihop communications using the IEEE 802.11 system. The proposed architecture was a mixture of two different types of networks: managed (master-and-slave) and ad-hoc (star). In this architecture, the participating nodes in each cluster communicated with each other via their respective access points (APs), which operated as mobile base stations. A network architecture was presented where APs could be utilised to communicate with other APs in an ad-hoc manner.
Chapter 25

Other

- ARP considered harmful: manycast transactions in ad hoc networks [299]
ARP handles neighbor discovery and address resolution in infrastructure networks, but is inadequate for mobile ad hoc networks (MANETs). Thus, many MANET routing protocols include a neighbor discovery mechanism. This separation of neighbor discovery and address resolution is a fundamental design problem that causes packet loss, particularly when the communication is manycast, a novel variant of multicast communication. Orozco-Lugo et al. proposed automatic address resolution, which moved address resolution into the routing protocol along with neighbor discovery, correcting these problems.

- A subspace-based active user identification scheme for CDMA ad hoc networks [300]
Lin and Lim proposed a novel spreading code scheme, Transmitter-Receiver-Based Code, for wireless ad hoc networks. A subspace-based active user identification algorithm based on the proposed spreading code design was introduced. The performance of the active user identifier was also studied by investigating the false alarm rate $P_f$ and miss rate $P_m$ with respect to the identifier threshold value $d_{th}$.

- Relative service differentiation for mobile ad hoc networks [301]
Chua et al. proposed a relative bandwidth service differentiation scheme for mobile ad hoc networks (MANETs). The service profile for a traffic session was defined as a relative target rate, which was a fraction of the effective link capacity of nodes. To calculate the effective link capacity of nodes in a randomly moving topology MANET, two methods were presented: one was parameter based and the other was measurement based calculations work effectively to estimate the effective link capacity of nodes and the relative service differentiation was consistent. Furthermore, the differentiation was more consistent when nodes used the measurement based calculation of link capacity because it was more accurate.
• RTS/CTS-induced congestion in ad hoc wireless LANs [302]
The RTS/CTS mechanism is widely used in wireless networks in order to avoid packet collisions and, thus, achieve high throughput. In ad hoc networks, however, the current implementation of the RTS/CTS mechanism may lead to interdependencies so that nodes become unable to transmit any packets during long periods of time. This effect manifests itself in the form of congestion where, after a certain point, the network throughput decreases with increasing load instead of maintaining its peak value. Ray et al. described and analyzed this problem in detail and provided a backward-compatible solution, called RTS validation. The simulations showed that this solution led to a 60% gain in the peak throughput in addition to stabilizing the throughput at high load.

• Service discovery based on multicast dns in ipv6 mobile ad-hoc networks [303]
Jeong et al. presented the mechanism for service discovery in IPv6 mobile ad-hoc networks, which used the multicast DNS. When a user knew a service name and its transport protocol, he or she could find the IPv6 address and the port number of the service through this mechanism. The user could find the service information of multicast service as well as that of unicast service. The authors also suggested the architecture of name service system not only for service discovery, but also for DNS name resolution.

• Priority polling with reservation wireless access protocol for multimedia ad hoc networks [304]
Tseng and Chen considered a new traffic source, priority data, to access the channel with the highest priority among conventional CBR, VBR and ABR sources. In order to achieve and maintain QoS guarantee for admitted CBR and VBR sources, a QoS guaranteed wireless access protocol, the priority polling with reservation (PPR) protocol that consisted of priority polling scheme (PPS) and randomly addressed polling (RAP) was proposed. The authors provided the jitter and delay constraints for CBR and VBR sources by reserving bandwidth for the mean PD sources that were active during the time to transmit CBR and VBR sources. The results showed that under the preemption of PD sources, the QoS constraints for CBR and VBR sources were guaranteed.

• Multi hop communication in global wireless framework [305]
Mobile ad-hoc networks are infrastructure-free highly dynamic wireless networks, where central administration or configuration by the user is impractical. Mingkhwan et al. highlighted the questions of allowing all the wireless ad hoc devices to use the same network address in a global wireless framework. It presented the paradigm of using auto-assigned, private non-internet-routable IP addresses as the basis to provide anytime, anywhere services to nomadic end users in the information space. It followed on from their work on integrating personal mobility services architectures and interoperating wireless net-
worked appliances. Providing a multi-hop communication over a series of user’s devices each acting as a multi-port MAC bridge constructed an interoperable, interworking domain allowing applications to run seamlessly in the upper layers. The authors discussed the case of the IEEE 802.11 protocol specification where the authors presented working scenarios and protocols used to initialise and maintain the operation of its multi-hop communications. It was an attempt to provide a better range of services in an interoperable heterogeneous domain to offering the services from both the network side and the local environment by means of multi-hop ad-hoc MAC bridges.

- Hop distances in homogeneous ad hoc networks [306]
  Bettstetter and Eberspacher investigated the discrete probability distribution of the minimum number of wireless hops $H$ between a random source and destination node. This topology attribute had significant impact on the network performance, e.g., on route discovery delay and message delivery. The authors derived closed form expressions for the probability that two nodes could communicate within $H = 1$ hop (i.e., via a direct link) or $H = 2$ hops (i.e., over one relay node). Connection paths with $H > 2$ hops and the expected hop distance $EH$ were studied by analytical bounds and extensive simulations.

- An analytical model for information retrieval in wireless sensor networks using enhanced APTEEN protocol [307]
  Manjeshwar et al. developed an $M/G/1$ model to analytically determine the delay incurred in handling various types of queries using their enhanced APTEEN (Adaptive Periodic Threshold-sensitive Energy Efficient sensor Network protocol) protocol. The protocol used an enhanced TDMA schedule to efficiently incorporate query handling, with a queuing mechanism for heavy loads. It also provided the additional flexibility of querying the network through any node in the network. To verify the analytical results, the authors simulated a temperature sensing application with a Poisson arrival rate for queries on the network simulator ns-2.

- Video transport over ad hoc networks: multistream coding with multipath transport [308]
  Mao et al. proposed to combine multistream coding with multipath transport, to show that, in addition to traditional error control techniques, path diversity provided an effective means to combat transmission error in ad hoc networks. The schemes that the authors examined were: 1) feedback based reference picture selection; 2) layered coding with selective automatic repeat request; and 3) multiple description motion compensation coding. All these techniques were based on the motion compensated prediction technique found in modern video coding standards. The authors studied the performance of these three schemes via extensive simulations using both Markov channel models and OPNET Modeler. To further validate the viability and performance advantages of these schemes,
the authors implemented an ad hoc multiple path video streaming testbed using notebook computers and IEEE 802.11b card. The results showed that great improvement in video quality could be achieved over the standard schemes with limited additional cost. Each of these three video coding/transport techniques was best suited for a particular environment, depending on the availability of a feedback channel, the end-to-end delay constraint, and the error characteristics of the paths.

- Multiple packet reception in wireless ad hoc networks using polynomial phase-modulating sequences [309]

Orozco-Lugo et al. proposed a blind interference cancellation algorithm that was able to provide multiple packet reception capability for asynchronous random access wireless mobile ad hoc networks. The algorithm exploited the fact that the baseband signal exhibited cyclostationarity properties, which were induced at the transmitters by means of modulating the symbols with polynomial phase sequences. This modulation did not expand the bandwidth and could be considered as a "color code" that could be used to distinguish one transmission from the others (i.e., packets from other users). The proposed technique did not require knowledge of the starting time of transmission of the desired signal and could also be applied to time-dispersive multipath channels. In addition, a practical way of assigning the color codes via the use of a common codebook known to all nodes was proposed, and the impact on local throughput of such a scheme was analyzed. Simulation results illustrated the excellent performance of the proposed approach.

- On the impact of IEEE 802.11 MAC on traffic characteristics [310]

IEEE 802.11 medium access control (MAC) is gaining widespread popularity as a layer-2 protocol for wireless local-area networks. While efforts have been made previously to evaluate the performance of various protocols in wireless networks and to evaluate the capacity of wireless networks, very little is understood or known about the traffic characteristics of wireless networks. Tickoo and Sikdar addressed the traffic characteristics of wireless networks and first developed an analytic model to characterize the interarrival time distribution of traffic in wireless networks with fixed base stations or ad hoc networks using the 802.11 MAC. The analytic model and supporting simulation results showed that the 802.11 MAC could induce pacing in the traffic and the resulting interarrival times were best characterized by a multimodal distribution. This was a sharp departure from behavior in wired networks and could significantly alter the second order characteristics of the traffic, which formed the second part of the study. Through simulations, the authors showed that while the traffic patterns at the individual sources were more consistent with long-range dependence and self-similarity, in contrast to wired networks, the aggregate traffic was not self-similar. The aggregate traffic was better classified as a multifractal process and the authors conjectured that the various peaks of the multimodal interarrival
time distribution had a direct contribution to the differing scaling exponents at various timescales.

- Multihop scatternet formation for Bluetooth networks [311]
  Basagni and Petrioli described a new protocol for the establishment of multihop ad hoc networks based on Bluetooth devices. The proposed solution was specification compatible, and achieved the following desirable properties, only a few of which were available in previous solutions. The protocol was executed at each node with no prior knowledge of the network topology, thus being fully distributed. The selection of the Bluetooth masters was driven by the suitability of a node to be the "best fit" for serving as a master. The generated topology (a scatter net, according to the Bluetooth terminology) was a connected mesh with multiple paths between any pair of nodes, thus achieving robustness. In contrast to existing protocols, the proposed solution did not assume any designated device to start the scatter net formation process and it is multihop in the precise sense that there is no requirement for each node to be in the transmission range of all the other nodes (one-hop networks).

- Ad hoc MPLS for virtual-connection-oriented mobile ad hoc networks [312]
  During the past few years, IP with multiprotocol label switching (MPLS) over WDM has emerged as the paradigm of choice for the future optical Internet. However, MPLS is complex and does not take into account mobility in wireless networks, so the current version of MPLS cannot be applied to wireless networks to establish connections in an end-to-end manner. Yeh proposed ad hoc MPLS, a light-weight version of MPLS with an ad hoc LSP (label switched path) extension for the realization of end-to-end virtual-connection-oriented ad hoc networks, which in turn enabled end-to-end QoS provisioning, traffic engineering and protection/restoration.

- Using Bluetooth for short-term ad hoc connections between moving vehicles: a feasibility study [313]
  Bluetooth is a promising wireless technology designed for short-range ad hoc connections, which has many potentially useful applications. One such use is the transfer of data between two fast-moving vehicles such as automobiles. Murphy et al. explored the suitability of Bluetooth to make connections in highly mobile environments. In particular, the authors developed a hardware testbed to make an empirical analysis of the time it takes to establish Bluetooth connections and the range at which those connections can be established. The authors also explored, by means of simulation, ways in which to improve connection setup times and the impact this will have on any potential data transfer.

- On the connectivity of wireless multihop networks with homogeneous and inhomogeneous range assignment [314]
Bettstetter investigated the connectivity of wireless multihop networks with uniformly randomly distributed nodes. The author analyzed the required transmission range that created, for a given node density, an almost surely $k$-connected topology. Besides scenarios in which each node had the same range, the author discussed inhomogeneous range assignments. The results were of practical value for the task of setting parameters in network-level simulations of ad hoc networks and in the design of wireless sensor networks.

- **Defining RF specifications for high density ad hoc networks: a probabilistic method** [315] Bernier and Senn presented a probabilistic method for evaluating the required RF (radio frequency) system specifications of high density ad hoc mobile networks. The method was based on a combination of RF system simulations and probabilistic models of expected interference. The analysis took into account the projected network density and its results were independent of small-scale movements of relative nodes. This method was extremely useful at the network planning stage since it showed how the technological limitations of RF receivers impacted the desired node density, and therefore capacity, of the ad hoc network.

- **Networked parking spaces: architecture and applications** [316] Finding a parking space is a common challenge faced by millions of city-dwellers every day. As common is the revenue generation by fee and fine collection in these municipalities. Wireless ad hoc networking technologies offer a new and efficient means to both simplify the process of parking and find collection as well as extending the convenience for drivers. Basu and Little described a multi-hop wireless parking meter network (PMNET) that, when coupled with a GPS receiver, allowed a user (driver) to quickly locate and navigate to an available parking space. The solution was achieved by equipping existing parking meters with wireless radio frequency (RF) transceivers and auxiliary hardware and software. The attractiveness of the proposal stemmed from the fact that such a network of nodes could function without any fixed wired or wireless infrastructure such as cellular or satellite networks. The authors modeled a PMNET as a special class of ad hoc networks characterized by a combination of static, immobile nodes (parking meters) and mobile nodes (vehicles). The authors proposed scalable techniques for satisfying a mobile user’s query in a distributed fashion. In particular, the authors made use of the static nature of the parking meters for efficient discovery and location based routing of information between them and users.

- **An adaptive management architecture for ad hoc networks** [317] Ad hoc networks, where mobile nodes communicate via multihop wireless links, facilitate network connectivity without the aid of any preexisting networking infrastructure.
The intrinsic attributes of ad hoc networks, such as dynamic network topology, limited battery power, constrained wireless bandwidth and quality, and large number of heterogeneous nodes, make network management significantly more challenging than stationary and wired networks. In particular, the conventional client/server-based manager/agent management paradigm falls short of addressing these issues. Shen described the Guerrilla management architecture to facilitate adaptive and autonomous management of ad hoc networks. The management capability of Guerrilla was scalable to accommodate the sheer number and heterogeneity of nodes, autonomous and survivable to adapt to network dynamics, and economical to minimize management overhead.

- Nonstop: continuous multimedia streaming in wireless ad hoc networks with node mobility [318]
  Guaranteeing continuous streaming of multimedia data from service providers to the users is a challenging task in wireless ad hoc networks, particularly when node mobility is considered. The topological dynamics introduced by node mobility are further exacerbated by the natural grouping behavior of mobile users, which leads to frequent network partitioning. Network partitioning posed significant challenges to the provisioning of continuous multimedia streaming services in wireless ad hoc networks, since the partitioning disconnects many mobile users from the centralized streaming service. Li and Wang proposed Nonstop, a collection of novel middleware-based run-time algorithms that ensured the continuous availability of such multimedia streaming services, while minimizing the overhead involved. The network-wide continuous streaming coverage was achieved by partition prediction and service replication on the streaming sources and assisted by distributed selection of streaming sources on regular mobile nodes and users. The proposed algorithms were validated by extensive results from performance evaluations.

- Noncooperative content distribution in mobile infostation networks [319]
  In wireless networks, it is often assumed that all nodes cooperate to relay packets for each other. Although this is a plausible model for military or mission-based networks, it is unrealistic for commercial networks and future pervasive computing environments. Yuen et al. addressed the issue of noncooperation between nodes in the context of content distribution in mobile infostation networks. All nodes had common interest in all files cached in the fixed infostations. In addition to downloading files from the fixed infostations, nodes acted as mobile infostations and exchanged files when they were in proximity. The authors stipulated a social contract such that an exchange occurred only when each node could obtain something it wanted from the exchange. The authors showed by analysis and simulations that network performance depended on node density, mobility and the number of files that were being disseminated. The results pointed to the existence of data diversity for mobile infostation networks. As the number of files of
interest to all users increased, the achievable throughput increased. Moreover, each user had a fairer share of the total network throughput. In particular, the transmission of each channel was only limited by contention, indicating the noncooperation strategy achieved near optimum resource utilization.

- **Simple, Accurate Time Synchronization for Wireless Sensor Networks [320]**
  Time synchronization is important for any distributed system. In particular, wireless sensor networks make extensive use of synchronized time in many contexts (e.g. for data fusion, TDMA schedules, synchronized sleep periods, etc.). Existing time synchronization methods were not designed with wireless sensors in mind, and need to be extended or redesigned. Sichitiu and Veerarittiphan’s solution centered around the development of a deterministic time synchronization method relevant for wireless sensor networks. The proposed solution featured minimal complexity in network bandwidth, storage and processing and could achieve good accuracy. Highly relevant for sensor networks, it also provided tight, deterministic bounds on both the offsets and clock drifts. A method to synchronize the entire network in preparation for data fusion was presented. A real implementation of a wireless ad-hoc network was used to evaluate the performance of the proposed approach.

- **Asymptotic distribution of the number of isolated nodes in wireless ad hoc networks with Bernoulli nodes [321]**
  Nodes in wireless ad hoc networks may become inactive or unavailable due to, for example, internal breakdown or being in the sleeping state. The inactive nodes cannot take part in routing(relaying and thus may effect the connectivity. A wireless ad hoc network containing inactive nodes is then said to be connected if each inactive node is adjacent to at least one active node and all active nodes form a connected network. Yi et al. assumed that the wireless ad hoc network consisted of \( n \) nodes, which were distributed independently and uniformly in a unit-area disk and were active (or available) independently with probability \( p \) for some constant \( 0 < p \leq 1 \). The authors showed that if all nodes had a maximum transmission radius \( r_n = \sqrt{\frac{\ln n + c}{npn}} \) for some constant \( c \), then the total number of isolated nodes was asymptotically Poisson with mean \( e^{-c} \) and the total number of isolated active nodes was also asymptotically Poisson with mean \( pe^{-c} \).

- **Robust wireless ad hoc networks [322]**
  Li et al. considered a large-scale of wireless ad hoc networks whose nodes were distributed randomly in a two-dimensional region \( \Omega \). Given \( n \) wireless nodes \( V \), each with transmission range \( r_n \), the wireless networks were often modeled by graph \( G(V, r_n) \) in which two nodes were connected if their Euclidean distance was no more than \( r_n \). The authors showed that, for a unit-area square region \( \Omega \), the probability \( G(V, r_n) \) being \( k \)-connected
was at least $e^{-e^{-\alpha}}$ when $n\pi r_n^2 \geq \ln n + (2k - 3) \ln \ln n - 2 \ln(k - 1)! + 2\alpha$ for $k > 1$ and $n$ sufficiently large. This result also applied to mobile networks when the moving of wireless nodes always generated randomly and uniformly distributed positions. The authors also conducted extensive simulations to study the practical transmission range to achieve certain probability of $k$-connectivity when $n$ was not large enough. The relation between the minimum node degree and the connectivity of graph $G(V, r)$ was also studied.

- Multiparty micropayments for ad hoc networks [323]
  The majority of ad hoc networks and their associated applications have been designed with closed user groups in mind. In such scenarios all the nodes in the network usually belong to a single authority and are configured to cooperate in the relaying of packets within the network. In recent years however, ad hoc networks have also found their way into everyday networking environments, where mobile devices may be under the administrative control of individual users. These users may not necessarily be motivated to provide services for free to others in the network. A typical situation could be where a node may wish to relay packets through a number of intermediate nodes in the ad hoc network, to access services in the fixed network. Tewari and O’Mahony presented a lightweight payment scheme based on hash chains, which allowed a node to pay others who relayed packets on its behalf in real-time. Also due to the dynamic nature of an ad hoc network, the topology of the network could change unpredictably. The design of the payment scheme was flexible enough to be able to cope with such route changes, without the need to contact a trusted third party such as a bank or broker to pay the nodes in the new path.

- Konark - a service discovery and delivery protocol for ad-hoc networks [324]
  The proliferation of mobile devices and the pervasiveness of wireless technology have provided a major impetus to replicate the network-based service discovery technologies in wireless and mobile networks. However, existing service discovery protocols and delivery mechanisms fall short of accommodating the complexities of the ad-hoc environment. They also place emphasis on device capabilities as services rather than device independent software services, making them unsuitable for m-commerce oriented scenarios. Helal et al. proposed Konark, a service discovery and delivery protocol designed specifically for ad-hoc, peer-to-peer networks, and targeted towards device independent services in particular. It had two major aspects - service discovery and service delivery. For discovery, Konark used a completely distributed, peer-to-peer mechanism that provided each device the ability to advertise and discover services in the network. The approach towards service description was XML based. It included a description template that allowed services to be described in a human and software understandable forms. A micro-HTTP server present on each device handled service delivery, which was based on SOAP. Konark provided a
framework for connecting isolated services offered by proximal pervasive devices over a wireless medium.

- The design of a spatial diversity model to mitigate narrowband and broadband interference in DSSS ad hoc networks [325]
  Spatial diversity has been gaining significant momentum in cellular systems due to its ability to improve radio links in mobile wireless channels. Techniques of spatial diversity have been expanded to build foundations for advanced antenna array technology, to increase capacity in mobile wireless communication systems due to radiation patterns that direct energy only in the intended direction, thereby greatly reducing interference. Similar benefits may be gained in DSSS ad hoc networks, though work in this area has been limited. To exploit spatial processing in future ad hoc networks, accurate array designs that embed spatial characteristics of the channel and radiation patterns are necessary to quantify the performance benefits. Therefore, Furman and Gerla designed a spatial diversity model and using simulation examined the performance benefits attained when configured in a DSSS ad hoc network, subject to channels with narrowband and broadband interference.

- Analytical derivation of the mean interference power in WLLNs & ad-hoc networks [326]
  Radio interference from adjacent systems or users is an important limiting quantity for the transmission rate in wireless communications. Interference studies, however, often have the drawback that they are obtained from measurements in a particular environment. A more generally valid characterization for the interference power is highly desirable. Hansen analytically derived such an expression for a single link. The derivation was based on a simple, well-accepted pathloss law; furthermore, on a geometrically motivated transformation of the properties of the environment into expressions that depended only on the volume and surface of the domain in which transmitter and receiver were randomly located. This strategy yielded a highly flexible and accurate approximation of the mean interference power as an analytical function of the key characteristics of wave propagation and the surroundings. The author shed also some light on the question why the stochastic radio channel was geometrically very robust.

- EWANT: the emulated wireless ad hoc network testbed [327]
  Sanghani et al. demonstrated a wireless 802.11 testbed. This testbed allowed for direct comparison between mobile wireless routing protocols without affecting their routing or MAC layer protocols or inter-layer interaction. The authors built a low cost environment to facilitate such wireless network research. The core idea was “compressing” the network and emulating mobility without actually moving the nodes. The authors successfully emulated the RF effects along with mobility. The viability of this test bed was checked
with the help of a click implementation of the dynamic source routing protocol. The experiences showed that such a testbed provided valuable feedback not available through simulation.

• Data flushing data transfer protocol for IEEE 802.11 ad hoc wireless network [328]

Sheu et al. presented a data flushing data transfer (DFDT) protocol for IEEE 802.11 wireless ad hoc network. The basic mechanism of DFDT was quite the same as the distributed coordination function (DCF) of the medium access control (MAC) of IEEE 802.11, which used a random access delay backoff time after a busy medium condition and RTS/CTS dialogue before sending actual payload data (direct data/ACK could also be used). The enhancement introduced by DFDT was mainly produced by the compilation process (CP), which fitted as many MAC layer packets as possible into one physical layer packet within the limit of a predetermined length. By using the CP, the authors lowered the protocol overhead, the packet arrival rate of the physical layer, and network contention all with one action. DFDT took the advantages of the RTS/CTS mechanism but had less the overhead. Simulation results backed by numerical analysis showed growing improvement in performance, limited by the saturation of the network, as the network load gets higher.

• Reputation propagation and agreement in mobile ad-hoc networks [329]

Several reputation systems have been proposed for mobile ad-hoc networks in order to stimulate cooperation among mobile nodes. However, whether or not the mobile nodes will agree on the reputation of other nodes is not studied. Liu and Yang presented a formal specification and analysis of a general class of mechanisms to locally update the reputation of mobile nodes. Given an initial assessment of the reputation of other mobile nodes, the authors formally showed that under mild conditions, the mobile nodes would achieve reputation agreement. The analysis captured reputation propagation using graph connectivity and makes use of a recent theoretical result [A. Jadbabaie, et. al., IEEE Control and Decision Conference, 2001]. The authors also evaluated the convergence speed of two reputation propagation mechanisms through simulations. The simulations showed that the speed of reputation propagation was an important factor for the convergence speed of reputation agreement.

• Ad hoc wireless network traffic-self-similarity and forecasting [330]

Liang studied the ad hoc wireless network traffic collected in an ad hoc network (AHN) testbed and showed that the ad hoc wireless network traffic was self-similar, which validated that AHN traffic was forecastable because self-similar time-series could be forecasted. The author applied a fuzzy logic system to ad hoc wireless network traffic forecasting and simulation results showed that it performed much better than did an LMS
adaptive filter. All these studies were very important for evaluating network capacity and determining the battery power mode based on the forecasted traffic workload.

- Distributed initialization algorithms for single-hop ad hoc networks with minislotted carrier sensing [331]

An ad hoc network is a self-organized and distributed entity, consisting of n mobile stations (MSs) without the coordination of any centralized access point. Initialization is one of the fundamental tasks to set up an ad hoc network, which involves assigning each of the n MSs a distinct ID number from 1 to n, distributedly. In Nakano et al. (2000), randomized initialization protocols are developed for single-hop ad hoc networks under different conditions. However, carrier sensing has not been utilized and suitable acknowledgment schemes for the algorithms are not developed. Moreover, the assumption taken by Nakano et al. about MSs being able to listen while transmitting is not valid for ad hoc networks. In this context, Cai et al. described two algorithms for initializing an ad hoc network with carrier sensing capability. First, a novel acknowledgment scheme was proposed for notifying a transmitting MS whether its transmission was successful during the initialization. Then, two distributed and randomized initialization algorithms were developed and analyzed, under the assumptions of a known and unknown number of users in the network, respectively. Both algorithms were obtained based on optimizing some key parameters to minimize the total time required to complete the initialization. Both theoretical analysis and simulations indicated that the proposed initialization algorithms outperformed the existing methods, in the sense that they took much less time to complete the initialization and the average number of transmission attempts before success was much smaller.

- The critical transmitting range for connectivity in sparse wireless ad hoc networks [332]

Santi and Blough analyzed the critical transmitting range for connectivity in wireless ad hoc networks. More specifically, the authors considered the following problem: assume n nodes, each capable of communicating with nodes within a radius of r, were randomly and uniformly distributed in a d-dimensional region with a side of length l; how large must the transmitting range r be to ensure that the resulting network was connected with high probability? First, the authors considered this problem for stationary networks, and the authors provided tight upper and lower bounds on the critical transmitting range for one-dimensional networks and nontight bounds for two and three-dimensional networks. Due to the presence of the geometric parameter l in the model, the results could be applied to dense as well as sparse ad hoc networks, contrary to existing theoretical results that applied only to dense networks. The authors also investigated several related questions through extensive simulations. First, the authors evaluated the relationship between the critical transmitting range and the minimum transmitting range that ensured formation of
a connected component containing a large fraction (e.g., 90 percent) of the nodes. Then, the authors considered the mobile version of the problem, in which nodes were allowed to move during a time interval and the value of r ensuring connectedness for a given fraction of the interval must be determined. These results yielded insight into how mobility affects connectivity and they also revealed useful trade-offs between communication capability and energy consumption.

- Integrating mobile IP with ad hoc networks [333]
  Extending traditional IEEE 802.11-based access points to incorporate the flexibility of mobile ad hoc networks would help make the dream of ubiquitous broadband wireless access a reality. Tseng et al. discussed several issues related to integrating the mobile Internet protocol with Manets.

- The use of multiuser detectors for multicasting in wireless ad hoc CDMA networks [82]
  Sankaran and Ephremides addressed the issue of performance of linear multiuser detectors for a multicasting application in an ad hoc wireless network. Using a code-division multiple-access (CDMA) framework, the authors demonstrated how capacity results for multiuser detectors could be adapted to do session admission control for the multicasting problem. The authors then developed a multicast routing algorithm for ad hoc wireless networks. Using the session admission control mechanism and the multicast routing algorithm, the authors evaluated the performance of three different linear multiuser detectors for the multicasting application.

- Opportunistic large arrays: cooperative transmission in wireless multihop ad hoc networks to reach far distances [334]
  The technique Scaglione and Hong propose allowed efficient flooding of a wireless network with information from a source, which the authors referred to as the leader. At the same time, it permitted us to transmit reliably to far destinations that the individual nodes were not able to reach without consuming rapidly their own battery resources, even when using multihop links (the reach-back problem). The synchronization constraints were extremely loose and could be fulfilled in a distributed manner. The key idea was to have the nodes simply echo the leader’s transmission operating as active scatterers while using adaptive receivers that acquired the equivalent network signatures corresponding to the echoed symbols. The active nodes in the network operated either as regenerative or nonregenerative relays. The intuition was that each of the waveforms would be enhanced by the accumulation of power due to the aggregate transmission of all the nodes while, if kept properly under control, the random errors or the receiver noise that propagated together with the useful signals would cause limited deterioration in the performance. The avalanche of signals triggered by the network leaders formed the so-called oppor-
tunistic large array (OLA). The main advantages of the OLA were its great flexibility and scalability.

- **Layernet: a self-organizing protocol for small ad hoc networks [335]**
  Huang et al. proposed a self-organizing protocol for small ad hoc networks. Among this protocol’s original features was the initial creation of an asynchronous sparse tree topology followed by a transition to a more fully connected network and synchronous scheduling. An efficient address bundling technique and unique reliability simulation results for this protocol were also presented.

- **Information-driven dynamic sensor collaboration [336]**
  Zhao et al. overviewed the information-driven approach to sensor collaboration in ad hoc sensor networks. The main idea was for a network to determine participants in a "sensor collaboration" by dynamically optimizing the information utility of data for a given cost of communication and computation. A definition of information utility was introduced, and several approximate measures of the information utility were developed for reasons of computational tractability. The authors illustrate the use of this approach using examples drawn from tracking applications.

- **Cross-layering in mobile ad hoc network design [337]**
  To overcome network performance problems, the MobileMan cross-layer design lets protocols that belong to different layers cooperate in sharing network-status information while still maintaining the layers’ separation at the design level.

- **Implementation of a lightweight service advertisement and discovery protocol for mobile ad hoc networks [338]**
  Service advertisement and discovery are important components for computing in mobile ad hoc network (MANET). Ma et al. implemented a lightweight protocol of service advertisement and discovery, which was based on a MANET multicast protocol ODMRP (On-Demand Multicast Routing Protocol). In this protocol, service advertisement and discovery information was piggybacked in ODMRP routing control packets. Simulation results of the implementation proved that the implementation workload and resource consumption of the protocol were lightweight.

- **Adaptive Modulation in Ad Hoc DS/CDMA Packet Radio Networks [339]**
  Souryal et al. investigated the benefit of adaptive modulation based on channel state information (CSI) in DS/CDMA multihop packet radio networks. By exploiting varying channel conditions on different links, adaptive modulation could be used in ad hoc networks to provide upper layers with higher capacity links over which to route traffic. Performance was evaluated in terms of the information efficiency, a new progress-related
measure for multihop networks. Three types of adaptivity were analyzed, differing in the level of CSI available: (i) full knowledge of the SIR at the receiver, (ii) knowledge of only the signal attenuation due to fading, and (iii) knowledge of only the slow fading component of the signal attenuation. The effect on performance of imperfect channel information was also investigated. Sample results were given for interference-limited networks experiencing fourthpower path loss with distance, Rayleigh fading, and lognormal shadowing.

- Improving Spatial Reuse of IEEE 802.11 Based Ad Hoc Networks [340]
  Ye et al. evaluated and suggested methods to improve the performance of IEEE 802.11 based ad hoc networks from the perspective of spatial reuse. Since 802.11 employed virtual carrier sensing to reserve the medium prior to a packet transmission, the relative size of the spatial region it reserved for the impending traffic significantly affected the overall network performance. The authors showed that the space reserved by 802.11 for a successful transmission was far from optimal and depending on the one hop distances between the sender and the receiver. The authors studied three scenarios with very different spatial reuse characteristics. The authors also introduced a new quantitative measure, the spatial reuse index, to evaluate the efficiency of the medium reservation accomplished by 802.11 virtual carrier sensing. The authors also proposed an improved virtual carrier sensing mechanism for wireless LAN scenarios and using analysis and simulation results, showed that it could significantly increase the spatial reuse and network throughput.

- Scalability in global mobile information systems (GloMo): issues, evaluation methodology and experiences [341]
  The GloMo (Global Mobile Information Systems) project1 has focused on developing new wireless ad hoc networking technologies. These new technologies rely on a broad and varied set of techniques to help cope with the problems inherent in the wireless environment. One of the most critical design elements of all the various technologies is their applicability in large scale deployments. Papavassiliou et al. aimed to develop and implement a simulation methodology to help evaluate the scalability of these new ad hoc networking technologies and gain some insight into the various aspects of ad hoc network performance scalability issues. To achieve that the authors developed a scalability performance evaluation framework and plan, that spanned all the various dimensions of scalability: size (number of nodes and density), traffic, operational environment (i.e. propagation models, terrain etc.), mobility. For demonstration purposes the authors applied this process on a representative integrated protocol suite designed to provide communication services in mobile ad hoc wireless networks. The corresponding results of the two most critical aspects of scalability properties in tactical networks (i.e. network initialization time and traffic scalability) were also presented, and demonstrated that a
very extensive evaluation of the corresponding scalability metrics under a combination of the various scalability dimensions defined in this paper, was necessary in order to provide an in-depth analysis of the scalability properties in wireless mobile ad hoc networking environments.

- Fault tolerant deployment and topology control in wireless ad hoc networks [342] Liu et al. considered a large-scale of wireless ad hoc networks whose nodes were distributed randomly in a two-dimensional region Ω (more specifically, a unit square). Given $n$ wireless nodes $V$, each with transmission range $r_n$, the wireless networks were often modeled by graph $G(V, r_n)$ in which two nodes were connected if and only if their Euclidean distance was no more than $r_n$. The authors first considered how to relate the transmission range with the number of nodes in a fixed area such that the resulted network could sustain $k$ fault nodes in its neighborhood with high probability when all nodes had the same transmission range. The authors showed that, for a unit-area square region $Ω$, the probability that the network $G(V, r_n)$ was $k$-connected was at least $e^{-e^{-n}}$ when the transmission radius $r_n$ satisfied $n \pi r_n^2 \geq \ln n + (2k - 3) \ln \ln n - 2 \ln(k - 1)! + 2\alpha$ for $k > 1$ and $n$ sufficiently large. This result also applied to mobile networks when the moving of wireless nodes always generated randomly distributed positions. The authors also conducted extensive simulations to study the practical transmission range to achieve certain probability the network being $k$-connectivity, when the number of nodes $n$ was not large enough. The relation between the minimum node degree and the connectivity of graph $G(V, r)$ was also studied. Setting the transmission range of all nodes to $r_n$ guaranteed the $k$-connectivity with high probability, but some nodes might have excessive number of neighbours in the graph $G(V, r_n)$. The authors then presented a localized method to construct a subgraph of the network topology $G(V, r_n)$ such that the resulting subgraph was still $k$-connected but with much fewer communication links maintained. The authors showed that the constructed topology had only $O(k \cdot n)$ links and was a length spanner. Here a graph $H \subseteq G$ was spanner for graph $G$, if for any two nodes, the length of the shortest path connecting them in $H$ was no more than a small constant factor of the length of the shortest path connecting them in $G$. Finally, The authors conducted some simulations to study the practical transmission range to achieve certain probability of $k$-connected when $n$ was not large enough.

- A new BlueRing scatternet topology for Bluetooth with its formation, routing, and maintenance protocols [343] The basic networking unit in Bluetooth is piconet, and a larger-area Bluetooth network can be formed by multiple piconets, called scatternet. However, the structure of scatternets is not defined in the Bluetooth specification and remains as an open issue at the designers’ choice. It is desirable to have simple yet efficient scatternet topologies with
good supports of routing protocols, considering that Bluetooths are to be used for personal area networks with design goals of simplicity and compactness. In the literature, although many routing protocols have been proposed for mobile ad hoc networks, directly applying them poses a problem due to Bluetooth’s special baseband and MAC-layer features. Lin et al. proposed an attractive scatternet topology called BlueRing, which connected piconets as a ring interleaved by bridges between piconets, and addressed its formation, routing, and topology-maintenance protocols. The BlueRing architecture enjoyed the following fine features. First, routing on BlueRing was stateless in the sense that no routing information needed to be kept by any host once the ring was formed. This would be favorable for environments such as Smart Homes where computing capability was limited. Second, the architecture was scalable to median-size scatternets easily (e.g. around 50-70 Bluetooth units). In comparison, most star- or treelike scatternet topologies could easily form a communication bottleneck at the root of the tree as the network enlarges. Third, maintaining a BlueRing was an easy job even as some Bluetooth units join or leave the network. To tolerate single-point failure, the authors proposed a protocol-level remedy mechanism. To tolerate multipoint failure, the authors proposed a recovery mechanism to reconnect the BlueRing. Graceful failure was tolerable as long as no two or more critical points fail at the same time. In addition, the authors also evaluated the ideal network throughput at different BlueRing sizes and configurations by mathematical analysis. Simulation results were presented, which demonstrated that BlueRing outperformed other scatternet structures with higher network throughput and moderate packet delay.

- Design and performance analysis of leader election and initialization protocols on ad hoc networks [344]
  Leader election and initialization are two fundamental problems in mobile ad hoc networks (MANETs). The leader can serve as a coordinator in the MANETs and the initialization protocol can assign each host a sequential, unique, and short ID. As we know, no research on initialization for IEEE 802.11-based MANETs has been done. Hsu and Sheu proposed two contention-based leader election and initialization protocols for IEEE 802.11-based single-hop MANETs. The authors also provided an efficient approach to evaluate the performance of the proposed protocols, such that the performance could be evaluated in polynomial time. The evaluation results provided a guideline to set the size of the contention window and thus improved the performance of the proposed leader election and initialization protocols. The results could also be used as a guideline to set the size of the contention window for any contention-based protocol. Simulation results justified that the evaluation results provided a good guideline to set the size of the contention window.

- IEEE 802.11 FHSS receiver design for cluster-based multihop video communications [345]
Recently, Ban and Gharavi proposed an ad hoc, cluster-based, multihop network architecture for video communications using IEEE 802.11 FHSS (Frequency Hopping Spread Spectrum) wireless LAN (WLAN) technology with 2GFSK (2-level Gaussian Frequency Shift Keying) modulation capable of 1 Mb/s transmission. To increase the transmission rate to 2 Mb/s for higher-quality video communications, the authors evaluated the performance of the IEEE 802.11 FHSS system when a 4GFSK modulation option is selected. Since the 2 Mb/s system utilizing 4GFSK modulation is not very efficient in terms of Radio Frequency (RF) range, to improve its performance for multihop applications a combination of diversity and noncoherent Viterbi equalizer are considered. For video transmission, the authors employed a bitstream-splitting technique together with a packet-based error-protection strategy to combat packet drops under multipath fading conditions. The real-time transport protocol (RTP), user datagram protocol (UDP), and Internet protocol (IP) are used for video streaming. This includes an RTP packetization scheme to control the packet size and to improve the error-resilient decoding of the partitioned video signal. The paper includes the simulation results showing the effects of the receiver design and diversity on the quality of the received video signals.

- *Internet connectivity for mobile ad hoc networks* [346]

The need for ad hoc networks arises when a number of mobile nodes gather in one particular location and form autonomous networks. Ad hoc networks can be adjoined to the Internet, introducing routing and addressing issues that require new features from ad hoc networking protocols. The Internet Gateway can offer global addressability and bidirectional Internet connectivity to every node in the ad hoc network. This can be done in such a way that mobile wireless nodes can migrate between wireless access points that have direct access to the wired Internet and the wireless ad hoc networks that do not have any such local access point infrastructure. Mobile IP can be employed to make such movement seamless (whenever physically possible), even though it occurs between domains with previously incompatible routing models. Perkins et al. believed that IPv6 and Mobile IPv6 afforded important advantages for making such attachments, especially regarding router advertisement and address autoconfiguration. The authors showed how general ad hoc networks can be connected to the Internet by Internet Gateways, and then described their specific experiments with Ad hoc On-Demand Distance Vector Routing (AODV) for IPv6 (AODV6). After demonstrating the basic principles allowing access to the Internet, the authors then detailed the further experiments using Mobile IPv6.
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