Title
Understanding The Interaction between Packet Forwarding and Channel Access in Multihop Wireless Networks

Author
Garcia-Luna-Aceves, J.J.

Publication Date
2010-11-08

Peer reviewed

Understanding The Interaction between Packet Forwarding and Channel Access in Multi-hop Wireless Networks

Xin Wang
wangxin@soe.ucsc.edu
Computer Engineering Department
University of California, Santa Cruz
Santa Cruz, CA 95064, USA

J.J. Garcia-Luna-Aceves
jj@soe.ucsc.edu
Computer Engineering Department
University of California, Santa Cruz
Santa Cruz, CA 95064, USA

Hamid R. Sadjadpour
hamid@soe.ucsc.edu
Electrical Engineering Department,
University of California, Santa Cruz
Santa Cruz, CA 95064, USA

***Abstract*—An analytical model is introduced for the study of the interplay between medium access control (MAC) and packet forwarding disciplines used in multi-hop wireless networks. The model incorporates the likelihood with which nodes access the channel, which is determined by the MAC protocol, and the creation of active portions of the topology, which is given by the packet forwarding discipline. The model allows the computation of per-node performance metrics for any given network topology and the combination of specific MAC protocols and packet forwarding methods. As an example of the applicability of our modeling framework, the analytical model is used to study the performance of multi-hop wireless networks using a contention-based MAC protocol (the IEEE 802.11 distributed coordination function) and a schedule-based MAC protocol (NAMA), together with different packet forwarding schemes in multi-hop networks. The analytical results derived from the model are validated with discrete-event simulations in Qualnet; the analytical results are shown to be very close to those attained by simulations.**

I. Introduction

In contrast to wired networks in which links work independently of others, the radio links of a wireless network are broadcast in nature and the traffic sent between a pair of nodes constitutes multiple access interference (MAI) for other nodes nearby. Consequently, scheduling and packet forwarding are far more interrelated to each other in a wireless network than in a wired network. The transmission schedule established by a MAC protocol defines in effect an "active link" between a transmitter and its intended receivers, while a route established by a routing protocol dictates the maintenance and continuous use of some links and the decay of others, and therefore impacts transmission schedules over such links.

An important limitation of current wireless network protocol designs is that the MAC and routing protocols are designed *in isolation*. Usually, a MAC or routing algorithm is evaluated under the setting of specific protocols interacting with it but designed and implemented independently from it. The results obtained through this method are *unilateral* and even *misleading*, e.g., can one MAC (routing) algorithm still perform well when combined with different routing (MAC) protocols? Why are there large performance difference for different MAC and routing protocol combinations? Considering that the entire protocol stack works as a single dynamic system, we cannot answer these and many similar questions without investigating the interplay between MAC and routing methods. Actually, the interaction between the MAC layer and the network layer is of paramount importance to the performance of wireless networks, as Section II indicates. Surprisingly, very little work has been reported in the analytical modeling of this interaction, and the vast majority of prior work has focused on simulations.

This paper introduces a modeling framework for the characterization of the performance attained with a MAC protocol working together with different packet forwarding disciplines on top of a realistic physical layer. Section III discusses the interactions between different protocol layers and the rationale for our modeling framework. Section IV presents our analytical model for the joint characterization of channel access and packet-forwarding functionalities using a realistic model for the physical layer.

The most popular approach for channel access in multi-hop wireless networks today is the IEEE 802.11 distributed coordination function (DCF) protocol. However, collision-free scheduled access to the channel is a valuable alternative from the standpoint of performance, because it reduces MAI. Accordingly, Section V and VI applies our modeling framework to the analysis of IEEE 802.11 DCF and a simple schedule-based MAC protocol (NAMA [1]) working together with different approaches for packet forwarding in multi-hop wireless networks.

Section VII validates the numerical results obtained with our analytical model by means of simulation experiments ran using the Qualnet simulator [2]. The results obtained via simulations in scenarios consisting of multi-hop networks of 50 and 100 nodes display a very good correlation with the results obtained

[1]This work was partially sponsored by the U.S. Army Research Office under grant W911NF-05-1-0246, by the National Science Foundation under grant CNS-0435522, by the Army Research Laboratory under the Network Science Collaborative Technology Alliance, Agreement No. W911NF-09-0053, and by the Baskin Chair of Computer Engineering. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the U.S. Government.

through our analytical model. We also analyzed how different packet forwarding disciplines interact with different channel access schemes to influence the system performance.

II. Related Work

A significant amount of work (e.g., [3] [4] [5] [6] [7] [8] [9] [10] [11] [12]) has been reported on the analytical modeling of contention-based MAC protocols. However, there are very few prior works discussing the interaction between MAC and packet forwarding in wireless networks, and most of them are based on the discussion of simulation results focusing on contention-based MAC protocols and single-path routing.

Das et al. [13] [14] use a simulation model to show that the interplay between routing and MAC protocols affects the performance significantly in the context of AODV and DSR. Royer et al. [15] explore the behavior of different unicast routing protocols when run over varying contention-based MAC protocols. They find that table-driven routing protocols behave in much the same way when used with different MAC protocols, while an on-demand routing protocol is more sensitive to the functionality of the MAC protocol, because it requires feedback mechanisms at the MAC layer.

Barrett et al. [16] conducted a comprehensive simulation study to characterize the interaction between MAC and routing protocols, node speed, and data rates in mobile ad-hoc networks. They concluded that no combination of MAC and routing protocol was better than other combinations over all mobility models and response variables.

Bai et al. [17] proposed a framework consisting of various protocol-independent metrics to capture interesting mobility characteristics, including spatial (temporal) dependence and geographic restrictions. They observed that the mobility pattern influences the connectivity graph that in turn influences the protocol performance. In addition, they did a preliminary investigation of the common building blocks of MANET routing protocols, the effect of mobility on these building blocks and how they influence the protocols as a whole.

Vadde et al. [18] studied the impact of QoS architectures, routing protocols, and MAC protocols on service delivery in MANETs, using interaction graphs to visualize the two-way interactions between factors. Vadde et al. [19] used statistical design of experiments to study the impact of factors and their interaction on the service delivery in a MANET. They considered the factors of QoS architecture, routing protocols, medium access control protocols, offered loads, and node mobility. Through statistical analysis of the simulation results, they found that the MAC protocol and its interaction with the routing protocol are the most significant factors influencing average delays, and that throughput is not much impacted by the type of routing protocol used.

A gap still remains on the modeling of multi-hop wireless networks under specific combinations of MAC protocols and packet-forwarding disciplines in a way that the impact of their interactions is taken into account in the performance evaluation of each node.

III. Protocol Interactions

In this section we address the interactions between protocols used in a stack and the classification of different feedback information.

The most important modeling factor in the interaction between the MAC layer and the physical layer is the *probability that a frame transmission is successful*, because it is the basis for the scheduling of either transmissions or retransmissions of frames by the MAC protocol.

The output of any routing protocol is a subset of nodes in the network, which forms a specific routing path, and this subset varies at different stages of routing protocol. For example, when there is no existing route, the subset includes every nodes that are involved in the route discovery (e.g., initiating route requests, sending route replies or forwarding routing control packets, etc.). After the route is established, the subset consists of the nodes that form a specific routing path or are responsible for the route maintenance. In this paper, we focus on the interaction of routing and MAC protocols that takes place *after* routes have been established. Accordingly, we are mainly interested on the interaction between the MAC protocol and the number of next-hops per destination, which are used according to specific forwarding rules. Our model captures this interplay by means of the *probability that a transmission schedule is collision-free*.

We classify the feedback information that flows across layers into two classes: (a) Feedback information that does not depend on the activity of other nodes (e.g., whether a node has data packets to send); and (b) feedback information dependent on the activities of all other nodes (e.g., the successful transmission probability of each frame, or the probability that a transmission schedule is collision-free). The MAC and physical (PHY) layers are coupled with each other tightly at small time scales encompassing just a few packet transmissions. On the other hand, route selections are made based on the end-to-end information between the traffic source and destination; hence, this activity interacts with the MAC layer at large time scales, i.e., many packet transmissions. Based on the above considerations, we investigate the interaction between protocol layers from small time scales (MAC and PHY) to large time scales (MAC and routing).

IV. Model Formulation

We assume that each node k transmits frames according to a transmission rate (transmission probability) τ_k, and retransmissions are independent of previous attempts. All nodes along the selected routing path always have packets to send (i.e., the transmission queue of each node is always nonempty). If there is more than one nodes transmitting to the same receiver simultaneously, the frame transmission is a failure.

A. Successful Frame Reception Probability

Let P_k^r denote the received signal power at node r for a signal transmitted by node k. Let V denote the finite set of $|V| = n$ nodes spanning the network under consideration, and $V_r \subseteq V$ the subset of nodes that are in the reception range of

node r. $V_r' \subseteq V_r$ is the subset of nodes that are on the selected routing path. V_r incorporates the topology information, while V_r' includes the feedback information from the network layer.

At time t, the signal-to-interference-plus-noise density ratio $SINR_i^r(t)$ for a signal transmitted by node i and received at node r is [20]:

$$\text{SINR}_i^r(t) = \frac{P_i^r(t)}{\sum_{j \in V_r'} \chi_j(t) P_j^r(t) + \sigma_r^2}, \tag{1}$$

where σ_r^2 is the background or thermal noise power at the front end of the receiver r. $\chi_j(t)$ is an on/off indicator,

$$\chi_j(t) = \begin{cases} 1, & \text{if } j \text{ transmits to } r \text{ at time } t, \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

$\chi_j(t)$ reflects MAC layer transmission scheduling(contention) results.

Let $|V_r'| = n_r$, there are exactly $2^{n_r - 1}$ combinations of active transmitting nodes (*interferers*) in V_r', excluding the transmitter i itself. In what follows, let $\{c_{ik}^r\}_{k=1,\ldots,2^{n_r-1}}$ denote the set of such combinations. Additionally, c_{i0}^r is the combination corresponding to the case when *no* interferers of *r* transmit.

Let $\gamma(c_{i0}^r)$ denote the SINR at node *r* for a bit transmitted by *i* when none of *r*'s interferers transmits:

$$\gamma(c_{i0}^r) = \frac{P_i^r L_i}{\sigma_r^2}, \tag{3}$$

where L_i is the spreading gain (or bandwidth expansion factor) of the spread-spectrum system.

If K is the length of the frame in bits, and $P_b(\gamma)$ is the bit-error probability for a certain SINR level γ, then the probability of successful frame reception ($f(c_{i0}^r)$) when only the sender transmits in the neighborhood of an intended receiver is:

$$f(c_{i0}^r) = \{1 - P_b[\gamma(c_{i0}^r)]\}^K. \tag{4}$$

The probability q that a transmitted packet does not collide equals the probability that no neighbor of the receiver transmits and the packet is received correctly (we do not consider the partial overlapping case in this paper). The probability that no neighbor transmits equals

$$P\{\text{no neighbor transmits}\} = \prod_{j \in V_r'} (1 - \tau_j) \tag{5}$$

Hence, using conditional probability, q can be expressed as

$$q = f(c_{i0}^r) \prod_{j \in V_r'} (1 - \tau_j) \tag{6}$$

We analyze the performance of the MAC layer following the approach introduced by Carvalho et al. [21] and Bianchi's model [22]. The MAC protocols we seek to model adjust their behavior dynamically according to the feedback information of the PHY and network layers to maximize the number of successful transmissions. Accordingly, we approximate the operation of the MAC protocols by assuming that these protocols in steady-state can be represented by a time-invariant function $h_i(\cdot)$ relating the successful transmission probability q_i with the steady-state scheduling rate τ_i,

$$\tau_i = h_i(q_i), i \in V, \tag{7}$$

where the subscript i in the mapping function $h_i(\cdot)$ denotes a node-specific instantiation of the MAC protocol in use.

Let $\mathcal{C}_i^r$ denote the random variable that indicates the occurrence of a specific combination c_{ik}^r of interferers. The probability that the set of active interferers is c_{ik}^r, i.e., $P\{\mathcal{C}_i^r = c_{ik}^r\}$ is a function of the MAC-dependent transmission probabilities τ_i,

$$P\{\mathcal{C}_i^r = c_{ik}^r\} = \prod_{m \in \overline{c_{ik}^r}} (1 - \tau_m) \prod_{n \in c_{ik}^r} \tau_n, \tag{8}$$

where $\overline{c_{ik}^r}$ denotes the complement set of c_{ik}^r, $V_r' - \{c_{ik}^r\}$.

The probability q_i *that a frame transmitted by* i *is successfully received* can be obtained as follows by considering the set $\{c_{ik}^r\}_{k=1,\ldots,2^{n_r-1}}$ of all possible combinations of active nodes in V_r':

$$\begin{aligned} q_i &= P\{\text{ successful frame reception }\} \\ &= \textstyle\sum_k P\{\text{ successful frame reception}, \mathcal{C}_i^r = c_{ik}^r\} \\ &= \textstyle\sum_k P\{\text{ succ. frame reception} \,|\, \mathcal{C}_i^r = c_{ik}^r\} P\{\mathcal{C}_i^r = c_{ik}^r\} \\ &= \textstyle\sum_k f(c_{ik}^r) P\{\mathcal{C}_i^r = c_{ik}^r\}, \end{aligned} \tag{9}$$

Recall that c_{i0}^r denotes the combinations corresponding to the case when *no* interferer of receiver *r* transmit, i.e., $c_{i0}^r = \{\emptyset\}$, meaning that $\overline{c_{i0}^r} = V_r'$, then we can approximate q_i as follows:

$$q_i \approx f(c_{i0}^r) P\{\mathcal{C}_i^r = c_{i0}^r\} \tag{10}$$

From Eq. (8),

$$q_i = f(c_{i0}^r) \prod_{j \in V_r'} (1 - \tau_j). \tag{11}$$

After the linear approximation using the Taylor series expansion (justified in [21]), we have

$$\tau_i = h_i(q_i) \approx a q_i, \quad \text{where} \quad a = h_i'(0), \tag{12}$$

From Eq. (12),

$$q_i = f(c_{i0}^r) \prod_{j \in V_r'} (1 - a q_j). \tag{13}$$

If we assume $a << 1$, and because $0 \leq q_i \leq 1$, we can approximate the previous products as follows:

$$q_i \approx f(c_{i0}^r) \left(1 - a \sum_{j \in V_r'} q_j\right) \tag{14}$$

From Eq. (12) and Eq. (14), we can obtain the functional form $h_i(q_i)$ by which the MAC layer relates the steady-state transmission probability τ_i with the successful transmission probability q_i.

B. End-to-End Throughput

Given that all nodes along an active path are assumed to be saturated, the average MAC layer one-hop throughput for any node i carrying traffic is

$$S_i = \frac{E\{\text{Data Payload}\}}{\overline{T_i}}. \tag{15}$$

where $\overline{T_i}$ is the average service time of node i. We note that since $\overline{T_i}$ varies across different nodes due to the topology information and traffic distributions, S_i is per-node throughput.

We denote the end-to-end throughput as

$$S_E = \min_{k=1}^{h_j} \{S_1, S_2, \ldots, S_k, \ldots, S_{h_j}\} \tag{16}$$

where h_j is the hop length of path j, S_k is the average one-hop throughput of hop k, defined in Eq. (15).

C. Interaction with Number and Type of Paths

Multipath routing protocols adapt different constraints for the establishment of next hops to destinations. The existing multipath routing protocols can be classified according to the type of paths they use:

1) Node-disjoint paths [23], which are paths to a destination in which a node appears in at most one path.
2) Link-disjoint paths [24] [25], which are paths to a destination in which the same pair of nodes defining a link can appear in at most one path.
3) Minimum-cost paths [26], which are paths to a destination that have the minimum cost amongst all available paths. These paths need not be link or node disjoint.

Because there is no standard definition of *minimum-cost* for multipath routing protocols, we focus on the study of node-disjoint routing and link-disjoint routing. We use Dijkstra's shortest path algorithm to form the multipath routing set. We choose hop-count as the routing distance metric. The first selected path is the one with the shortest distance between the source and the destination. A path will be added to the selected routing set if: (a) it has the shortest distance among all the unselected paths; and (b) it satisfies the node-disjoint or link-disjoint constraint with previous selected paths. If there are more than one path with the same distance, we assume that the path with the smaller IP address is selected. This process is continued until no more paths can be added.

In our modeling framework, the routing information is fed into V_r', c_{ik}^r and S_E^f, separately. We extend the definition of *interference matrix* [21] to take into account the effect of routing factors. As indicated in Eq. 11, in order to calculate q_i, we need to know the set of interferers for each transmitter-receiver pair. We select a node as a potential interferer if and only if: (a) The received interference signal power at the receiver is above the carrier sensing threshold, as indicated in [21]; and (b) it is on at least one of the routing paths.

D. Interaction with Packet Forwarding Disciplines

Once routing paths are formed, nodes use different forwarding rules to select their successors. Opportunistic routing protocols [27] [28] have been proposed to exploit the benefits of cooperative diversity and path diversity techniques. To simplify our analysis, we classify the different routing forwarding rules into the following types:

1) Single-copy forwarding: A node selects its neighbor with the smallest distance to the destination as the successor, and the smallest address is chosen if there are multiple successors with the same distance.
2) Multiple-copy forwarding: A node selects all successors for forwarding to a destination.
3) P-persistent opportunistic forwarding: A node selects a given successor to forward a packet towards a destination with a probability p_f.

As in Section IV-C, the routing forwarding rule impacts the calculation of $SINR_i^r(t)$, c_{ik}^r and q_i, which influences the conditional probability of successful frame reception ($f(c_{i0}^r)$) and the mapping function $h_i(.)$.

V. Modeling Contention-Based MAC: 802.11 DCF

We extend the prior model proposed by Carvalho et al. [21] and Bianchi's model [22] to study the interactions between IEEE 802.11 DCF and different packet forwarding methods.

Given the backoff time characterization in 802.11 DCF, the *average service time* is $\overline{T} = \overline{T}_B + \overline{T}_S$, where $\overline{T}_B$ is the average backoff time, $\overline{T}_S$ is the average time to successfully transmit a packet at the end of the backoff operation. In order to obtain $\overline{T}_B$, $\overline{T}_S$, we first need to calculate the probability that a transmission is successful (p_s^i), the probability that the channel is idle (p_i^i), and the probability that a collision occurs (p_c^i).

The transmission probability τ_i of each node i is [21]

$$\tau_i = \frac{2[1-2(1-q_i)]}{[1-2(1-q_i)](W_{\min}+1)+(1-q_i)W_{\min}(1-(1-q_i)^m)} \tag{17}$$

where $W_{\min}$ is the minimum contention window size specified for the backoff operation, m is the standard-defined maximum power used to set up the maximum contention window size, i.e., $W_{\max} = 2^m W_{\min}$.

Eq. (17) gives us the functional form $h_i(q_i)$ by which the MAC layer relates the steady-state transmission probability τ_i with the successful transmission probability q_i. Then we can derive a first-order approximation for it using a Taylor series expansion and express τ_i in terms of q_i as

$$\tau_i(q_i) = \frac{2W_{\min}}{(W_{\min}+1)^2} q_i. \tag{18}$$

When we consider all nodes in the topology, this can be rewritten in matrix notation $\boldsymbol{\tau} = a\mathbf{q}$, where $\boldsymbol{\tau} = [\tau_1\ \tau_2\ \ldots\ \tau_n]^T$, $a = 2W_{\min}/(W_{\min}+1)^2$, and $\mathbf{q} = [q_1\ q_2\ \ldots\ q_n]^T$.

The probability that there exists some node from V_r' transmitting a frame while node i is in backoff is

$$p_{tr}^i = 1 - \prod_{j \in V_r'} (1-\tau_j) \tag{19}$$

The probability p_{suc}^i that a transmission is successful is the probability that some node in V_r' transmits successfully,

conditioned on the fact that at least one node in S_i attempted to transmits, i.e.,

$$p^i_{suc} = \frac{\sum_{k\in S_i} P\{k \text{ succeed} \,|\, k \text{ transmits}\} P\{k \text{ transmits}\}}{p^i_{tr}} = \frac{\sum_{k\in S_i} q_k \tau_k}{p^i_{tr}} \quad (20)$$

Then, according to Bianchi's model [22], the probability that a transmission is successful is $p^i_s = p^i_{tr} p^i_{suc}$; the probability that the channel is idle is $p^i_i = 1 - p^i_{tr}$, and the probability that a collision occurs is $p^i_c = p^i_{tr}(1 - p^i_{suc})$. We can further derive $\overline{T}_B$ and $\overline{T}_S$ using p^i_s, p^i_i and p^i_c according to the methods described in [22].

VI. Modeling Schedule-Based MAC: NAMA

We choose NAMA [1] [29] as an example of schedule-based MAC schemes, because it completely eliminates the communication overhead of building a dynamic channel access schedule, except for collecting two-hop neighborhood information, which is minimal overhead compared with the task of collecting complete network topology information. In NAMA, a hash function is implemented at each node. The hash function takes a distinctive string of a node as input, and derives a random priority for each neighbor within two hops. The distinctive input string is the concatenation of the corresponding node identifier (collected through periodical HELLO messages) and the current time slot number such that the priority changes in different time slot. The channel access eligibility of each node is then determined by the node comparing its own priority with those of the nodes in its two-hop neighborhood. If a node has the highest priority, the node can access the channel within the corresponding time slot, while its one- and two-hop neighbors are forbidden from channel access because they have lower priorities than the node.

In order to find the correlation between the steady-state MAC layer scheduling rate (τ_i) and the successful transmission probability q_i, we first define the probability that the transmission schedule for node i is collision-free (ϕ_i) as follows:

$$\phi_i = P_{\{no\_conflicts|success\_info\}} P_{success\_info} \quad (21)$$

where $P_{success\_info}$ is the probability that the neighborhood information exchange is successful in i's two-hop range. $P_{\{no\_conflicts|success\_info\}}$ is the conditional probability of conflict-free scheduling given the correct neighbor information. For simplicity, We assume that any unsuccessful information exchange leads to transmission collisions.

Then

$$\tau_i = \phi_i q_i \quad (22)$$

The time frame of NAMA can be further divided into a signal section and a data section. We denote the length of a time frame as

$$T_f = N_{signal} t_{signal} + N_{data} t_{data}, \quad (23)$$

where t_{signal}, t_{data} are the signal and data slot length; N_{signal}, N_{data} are the number of signal and data slots, respectively.

Then according to Equation 6,

$$P_{success\_info} = f(c^r_{i0}) P\{\text{no neighbor transmits}\} \quad (24)$$

In NAMA, each node randomly picks up a signal slot in the signal section to exchange neighborhood information.

$$P\{\text{no neighbor transmits}\} = (1 - \frac{1}{N_{signal}})^{N^i_2 - 1} \quad (25)$$

where N^i_2 is the number of neighbors within two hops of i.

The conditional probability of node i winning the node election given the correct neighborhood information is:

$$p^i_s = \frac{1}{N^i_2} \quad (26)$$

Because NAMA uses the node identifier and the current time slot number as input to derive a random priority for every neighbor, which is unique within two hops, it eliminates the conflict scheduling given the correct neighborhood information.

$$P_{\{no\_conflicts|success\_info\}} = 1 \quad (27)$$

$$\phi_i = p^i_s P_{success\_info} \quad (28)$$

From Eq. (22) (24) (25) (28), we can obtain the correlation between τ_i and q_i.

Given that the average number of times node i could transmit successfully in one time frame is $\lceil \tau_i N_{data} \rceil$, the average service time is

$$\overline{T} = \frac{T_f}{\lceil \tau_i N_{data} \rceil} \quad (29)$$

VII. Model Validation

A. Simulation Settings

We compare the numerical results with the simulation results obtained from Qualnet [2]. The detailed simulation settings can be found in Table I. The packet length used is 1500 bytes. The duration of the simulation is 100 seconds. For the system throughput results, the simulations are repeated with ten different seeds to average the results for each scenario.

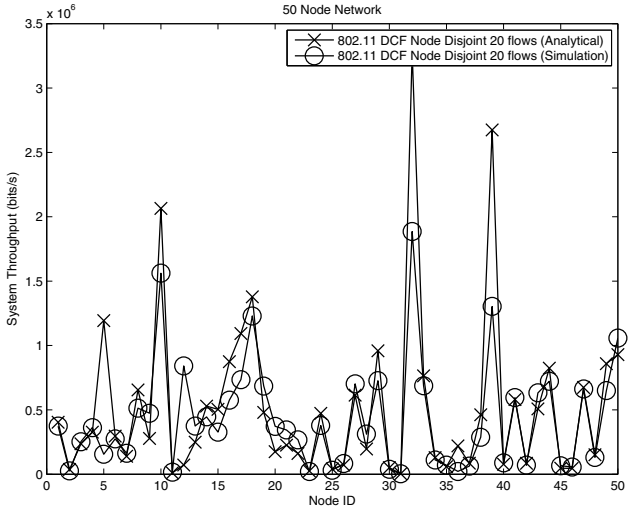
We validate the numerical results against simulation experiments under two scenarios. The first scenario consists of 50 nodes distributed randomly across a 500 × 500 square meters area. The second scenario consists of 100 nodes distributed across a 800 × 800 square-meter area. The only constraint for the topology generation is that the network needs to be connected. For each topology, we set up multiple multi-hop CBR flows and vary the number of CBR flows to investigate the influence of packet forwarding methods.

B. Interaction between Multipath Routing and MAC

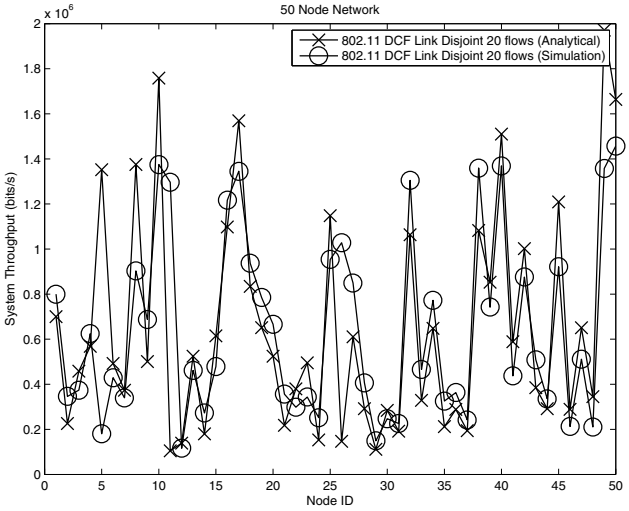
We first examine the interaction of multipath routing formation and different MAC protocols.

TABLE I
SIMULATION PARAMETERS

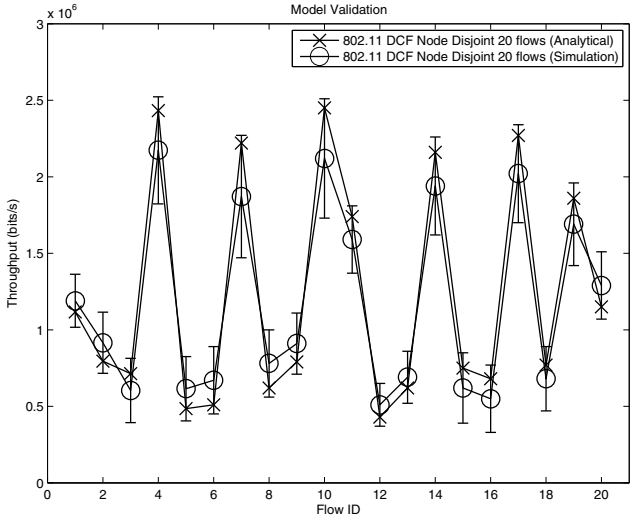
802.11 DCF MAC		NAMA MAC		PHY	
$W_{\min}$	15	t_{signal} (μs)	142	Transmission rate (Mbps)	54
$W_{\max}$	1023	N_{signal}	500	Transmission Power (dBm)	16
RTS (bytes)	30	t_{data} (μs)	362.2	Sensitivity of PHY (dBm)	-69
CTS (bytes)	24	N_{data}	1000	Path loss factor (α)	4
ACK (bytes)	24			Transmission range (m)	79.58
MAC Header (bytes)	34			Temperature (Kelvin)	290
Slot Time (μsec)	9			Noise Factor	10
SIFS (μsec)	16				



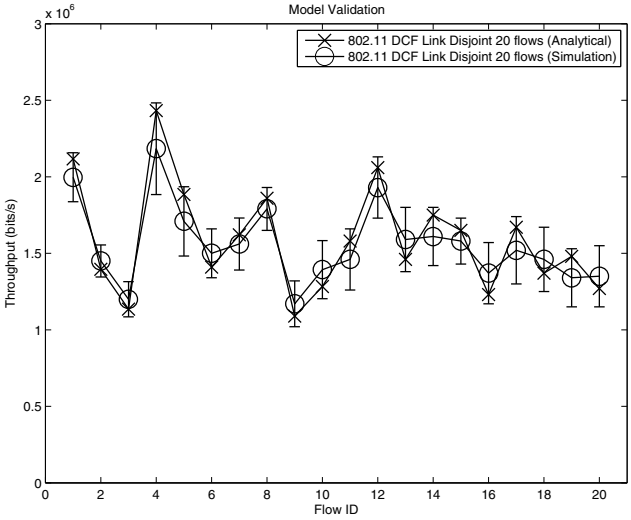
(a) 802.11 DCF with Node-Disjoint Routing Per-node Throughput (50 Nodes Network)



(b) 802.11 DCF with Link-Disjoint Routing Per-node Throughput (50 Nodes Network)



(c) 802.11 DCF with Node-Disjoint Routing Per-flow Throughput (50 Nodes Network, 20 Flows)



(d) 802.11 DCF with Link-Disjoint Routing Per-flow Throughput (50 Nodes Network, 20 Flows)

Fig. 1. Model Validation: 802.11 DCF

TABLE II
802.11 DCF SYSTEM THROUGHPUT WITH DIFFERENT MULTIPATH PACKET FORWARDING

50 nodes	Node-disjoint (analytical) (Mb/s)	Node-disjoint (simulation) (Mb/s)	Link-disjoint (analytical) (Mb/s)	Link-disjoint (simulation) (Mb/s)
10 flows	32.12	28.24	32.55	33.17
20 flows	29.97	28.13	32.65	30.26
30 flows	25.19	23.37	29.99	27.45
100 nodes	Node-disjoint (analytical)	Node-disjoint (simulation)	Link-disjoint (analytical)	Link-disjoint (simulation)
20 flows	64.01	59.74	81.99	79.23
30 flows	65.21	61.21	77.04	81.49
40 flows	68.43	64.35	82.07	86.34

1) 802.11 DCF: To demonstrate the model accuracy and provide some insights on system performance, we first examine the per-node throughput of 802.11 DCF, as Fig. 1 shows. Comparing Fig. 1(a) and Fig. 1(d), we observe that link-disjoint routing balances the traffic more evenly across different nodes. In other words, it is relatively easier to form congestion (bottlenecks) using node-disjoint routing.

Because link-disjoint routing has a better spatial reuse throughout the network, it helps to form a better transmission scheduling at the MAC layer. This effect is amplified by a contention-based MAC. When we revisit the analytical model procedure shown in Eq. (1)-(21), the larger the contention neighbor set V_r', C_i^r, the lower the probability that a frame the transmission is successful, the lower the probability that a transmission schedule is collision free. The network-level congestions introduced by the routing protocols will introduce more contentions at the MAC layer, and the contention overheads around the bottlenecks will degrade the system performance significantly.

For the above reasons, link-disjoint routing always outperforms node-disjoint routing when interacting with contention-based MACs, as Table II shows.

2) NAMA: In contrast to contention-based MAC protocols, when a schedule-based MAC interacts with different multipath packet forwarding disciplines, there is no significant difference between node-disjoint routing and link-disjoint routing. This is shown in Fig. 2 and Table III.

Revisiting the modeling process of the schedule-based MAC (Eq. (21)), its performance is mainly dependent on two factors: (a) The probability that the topology information exchange is successful; and (b) the conditional probability that a transmission schedule is collision-free given the correct topology information. Although the first factor is partially decided by the number of contending nodes, the contention overheads will not increase linearly with the intensity of contentions, as contention-based MACs do. In other words, channel access contention may influence how quickly the collision-free transmission schedule is formed, while it does not influence the system throughput over the long-time run if the schedule mechanism works correctly.

Another reason why schedule-based MAC protocols are insensitive to the behavior of the routing protocol in our model is that the schedule rule is to increase the spatial/time reuse in the two-hop range to the largest extent, which alleviates the congestion introduced by routing protocols, if there are any.

3) Model accuracy: To validate the per-node performance accuracy of the analytical model, we weigh the prediction error with respect to the dynamic range of throughput values obtained in simulations. Through counting the number of nodes within a certain percentage prediction error, we obtain the the error prediction distribution for each simulation experiment. Due to page limits, we did not enumerate the error prediction distribution results for all the simulations in this chapter. The detailed results can be found in [30]. We find that the percentage of prediction error is within 20% in about 90% of the nodes and within 10% in about 80% of the nodes, showing how close our analytical model is in predicting the results obtained in simulations.

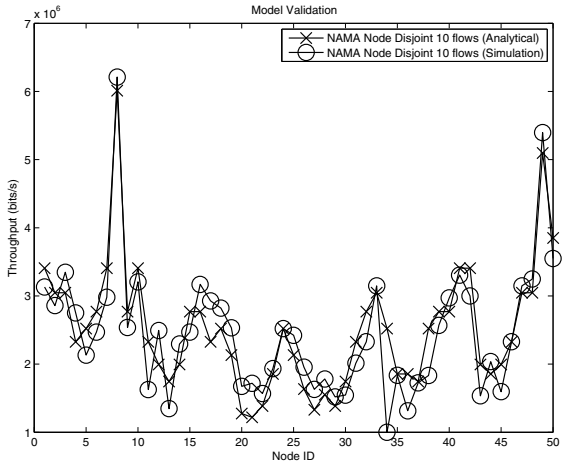
C. Interaction between opportunistic forwarding and MAC

We now examine the impact of packet forwarding rules on different MAC protocols. For opportunistic forwarding, we vary different p_f values. As Table IV-Table VII show, multiple-copy forwarding degrades system throughput while opportunistic forwarding could improve system throughput to some extent.

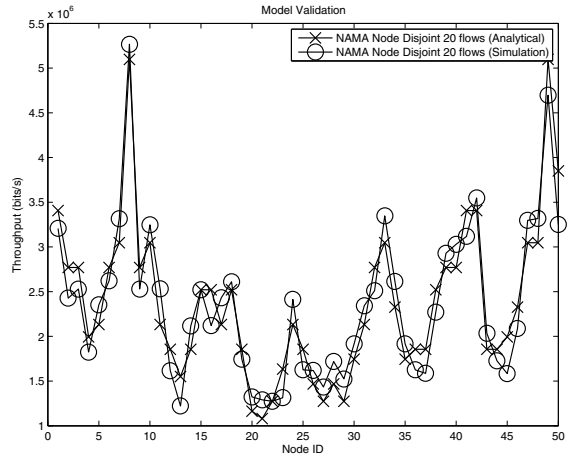
1) 802.11 DCF: The system throughput comparisons of 802.11 DCF under different packet forwarding rules are shown in Table IV and Table V. We observe that, when combined with 802.11 DCF, opportunistic forwarding could enhance the system throughput for some p_f.

2) NAMA: The system throughput results for NAMA using different packet forwarding rules are shown in Table VI and Table VII. We observe that, in contrast to the results shown in Table IV, when combining NAMA with opportunistic forwarding, the improvement of system throughput is quite small.

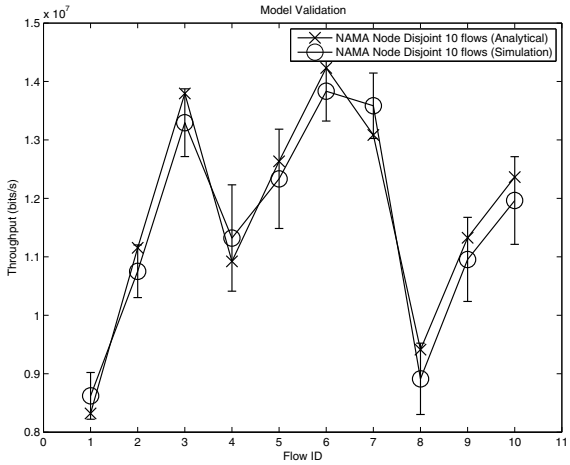
To understand the reason for the differences in the results obtained with 802.11 DCF and NAMA, we need to revisit how opportunistic forwarding impacts the system performance. First, opportunistic forwarding increases the system reliability by using multiple successors to forward duplicate packets. This is at the cost of consuming more system resources, which is the major reason that single-copy forwarding always outperforms multi-copy forwarding in terms of throughput. Second, one key aspect of opportunistic forwarding is that the node that forwards a packet is determined on-the-fly, which means that the contention neighbor sets V_r' and C_i^r change over time. This is desirable when a contention-based MAC is used, because it increases the robustness of the end-to-end transmissions and could accommodate channel fluctuations. However, it is more



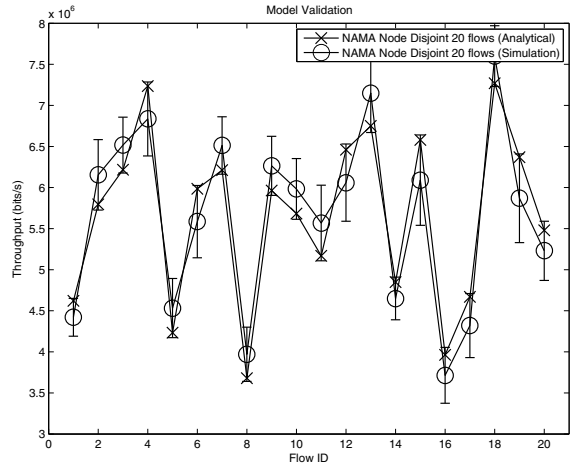
(a) NAMA with Node-Disjoint Routing Per-Node Throughput(50 Nodes Network, 10 flows)



(b) NAMA with Node-Disjoint Routing Per-Node Throughput (50 Nodes Network, 20 flows)



(c) NAMA with Node-Disjoint Routing Per-flow Throughput(50 Nodes Network, 10 flows)



(d) NAMA with Node-Disjoint Routing Per-flow Throughput (50 Nodes Network, 20 flows)

Fig. 2. Model Validation: NAMA

TABLE III
NAMA SYSTEM THROUGHPUT WITH DIFFERENT MULTIPATH PACKET FORWARDING

50 nodes	Node-disjoint (analytical) (Mb/s)	Node-disjoint (simulation) (Mb/s)	Link-disjoint (analytical) (Mb/s)	Link-disjoint (simulation) (Mb/s)
10 flows	125.54	117.29	123.27	121.03
20 flows	118.81	114.42	118.81	118.98
30 flows	116.02	112.13	115.78	116.37
100 nodes	Node-disjoint (analytical)	Node-disjoint (simulation)	Link-disjoint (analytical)	Link-disjoint (simulation)
20 flows	351.80	341.23	323.07	337.15
30 flows	320.94	313.42	314.85	316.38
40 flows	307.59	309.78	301.97	306.42

TABLE IV
802.11 DCF SYSTEM THROUGHPUT WITH DIFFERENT ROUTING FORWARDING RULES

50 nodes	Single-copy forwarding (analytical) (Mb/s)	Single-copy forwarding (simulation) (Mb/s)	Multiple-copy forwarding (analytical) (Mb/s)	Multiple-copy forwarding (simulation) (Mb/s)
10 flows	22.38	21.75	16.28	16.59
20 flows	20.09	19.26	16.33	15.14
30 flows	18.41	18.78	14.99	13.73
100 nodes	Single-copy forwarding (analytical) (Mb/s)	Single-copy forwarding (simulation) (Mb/s)	Multiple-copy forwarding (analytical) (Mb/s)	Multiple-copy forwarding (simulation) (Mb/s)
20 flows	64.01	59.74	41.99	36.62
30 flows	65.20	61.26	38.52	41.75
40 flows	68.43	64.35	41.04	43.17

TABLE V
802.11 DCF SYSTEM THROUGHPUT WITH DIFFERENT OPPORTUNISTIC FORWARDING (p_f)

50 nodes	$p_f = 0.2$ (analytical) (Mb/s)	$p_f = 0.2$ (simulation) (Mb/s)	$p_f = 0.4$ (analytical)(Mb/s)	$p_f = 0.4$ (simulation) (Mb/s)
10 flows	26.76	28.09	24.25	22.62
20 flows	25.15	26.17	22.78	24.47
30 flows	25.03	24.72	21.96	24.08
50 nodes	$p_f = 0.6$ (analytical) (Mb/s)	$p_f = 0.6$ (simulation) (Mb/s)	$p_f = 0.8$ (analytical) (Mb/s)	$p_f = 0.8$ (simulation) (Mb/s)
10 flows	21.09	22.55	18.43	19.13
20 flows	19.27	20.76	17.06	17.88
30 flows	18.45	19.87	15.11	16.52
100 nodes	$p_f = 0.2$ (analytical) (Mb/s)	$p_f = 0.2$ (simulation) (Mb/s)	$p_f = 0.4$ (analytical)(Mb/s)	$p_f = 0.4$ (simulation) (Mb/s)
20 flows	76.18	79.69	67.26	71.25
30 flows	75.27	78.85	65.13	69.23
40 flows	78.31	78.26	66.89	69.28
100 nodes	$p_f = 0.6$ (analytical) (Mb/s)	$p_f = 0.6$ (simulation) (Mb/s)	$p_f = 0.8$ (analytical) (Mb/s)	$p_f = 0.8$ (simulation) (Mb/s)
20 flows	59.22	63.54	49.04	48.15
30 flows	60.91	62.08	45.16	41.21
40 flows	58.34	62.99	46.60	43.12

TABLE VI
NAMA SYSTEM THROUGHPUT WITH DIFFERENT ROUTING FORWARDING RULES

50 nodes	Single-copy forwarding (analytical) (Mb/s)	Single-copy forwarding (simulation) (Mb/s)	Multiple-copy forwarding (analytical) (Mb/s)	Multiple-copy forwarding (simulation) (Mb/s)
10 flows	96.02	91.08	61.64	66.53
20 flows	92.11	86.39	59.40	55.49
30 flows	86.25	82.01	57.89	53.26
100 nodes	Single-copy forwarding (analytical) (Mb/s)	Single-copy forwarding (simulation) (Mb/s)	Multiple-copy forwarding (analytical) (Mb/s)	Multiple-copy forwarding (simulation) (Mb/s)
20 flows	265.14	254.39	161.54	168.58
30 flows	243.28	231.76	157.43	149.19
40 flows	214.87	203.91	150.99	143.21

TABLE VII
NAMA SYSTEM THROUGHPUT WITH DIFFERENT OPPORTUNISTIC FORWARDING (p_f)

50 nodes	$p_f = 0.2$ (analytical) (Mb/s)	$p_f = 0.2$ (simulation) (Mb/s)	$p_f = 0.4$ (analytical)(Mb/s)	$p_f = 0.4$ (simulation) (Mb/s)
10 flows	98.10	104.28	83.37	80.19
20 flows	96.35	100.02	80.29	84.45
30 flows	88.24	96.23	78.06	81.27
50 nodes	$p_f = 0.6$ (analytical) (Mb/s)	$p_f = 0.6$ (simulation) (Mb/s)	$p_f = 0.8$ (analytical) (Mb/s)	$p_f = 0.8$ (simulation) (Mb/s)
10 flows	75.16	79.85	66.26	70.24
20 flows	72.32	71.58	68.84	66.59
30 flows	70.35	68.73	64.56	68.16
100 nodes	$p_f = 0.2$ (analytical) (Mb/s)	$p_f = 0.2$ (simulation) (Mb/s)	$p_f = 0.4$ (analytical)(Mb/s)	$p_f = 0.4$ (simulation) (Mb/s)
20 flows	270.18	262.39	231.04	225.01
30 flows	246.23	234.85	217.50	219.74
40 flows	219.72	231.80	202.59	210.88
100 nodes	$p_f = 0.6$ (analytical) (Mb/s)	$p_f = 0.6$ (simulation) (Mb/s)	$p_f = 0.8$ (analytical) (Mb/s)	$p_f = 0.8$ (simulation) (Mb/s)
20 flows	196.16	182.40	182.55	178.14
30 flows	185.24	170.16	180.61	172.06
40 flows	183.44	174.33	176.18	169.58

difficult for a schedule-based MAC to build a collision-free transmission schedule. What is more, the schedule-based MAC also alleviates the collisions of transmissions and physical-layer interference to some extent. As a result, the gain of the opportunistic forwarding is reduced when combined with a schedule-based MAC, as Table VI shows. Given that most opportunistic routing schemes have been evaluated over contention-based MAC (802.11 DCF or its extensions) [27] [28], the results obtained in this paper motivate us to rethink how to leverage opportunistic forwarding using generic MAC protocols.

From Table V and Table VII, we can also find the system throughput does not increase linearly with p_f. This is because a larger p_f not only increases the reliability of end-to-end delivery, but also the contentions within the two-hop range. For each simulation experiment, there is an optimal p_f, which is dependent on the topology and the traffic pattern.

VIII. CONCLUSION

We introduced an analytical model to study the interactions of MAC and packet forwarding schemes in multi-hop wireless networks. Our model captures different aspects of the protocol interaction procedure and different information feedback across layers, and permits us to study how the use of multiple paths and packet forwarding rules influence the performance of different MAC protocols. We validated our analytical model by comparing its results against simulation experiments. Given the good match between analytical and simulation results, it follows that the results obtained from the analytical model can provide valuable insights on the interaction between MAC and routing protocol and how protocol stacks could be optimized.

REFERENCES

[1] L. Bao and J. J. Garcia-Luna-Aceves, "A New Approach to Channel Access Scheduling for Ad Hoc Networks," in *ACM Seventh Annual International Conference on Mobile Computing and networking(Mobicom)*, 2001.

[2] Qualnet Simulator, "Scalable Network Technologies, http://www.scalable-networks.com/."

[3] H. Kim and J. C. Hou, "Improving protocol capacity with model-based frame scheduling in IEEE 802.11-operated WLANs," in *Proc. of the 9th ACM International Conference on Mobile Computing and Networking (MOBICOM)*, San Diego, CA, USA, September 2003, pp. 190–204.

[4] I. Gitman, "On the capacity of slotted ALOHA networks and some desigh problems," *IEEE Trans. on Communications*, vol. COM-23, no. 3, pp. 305–317, Mar 1975.

[5] F. A. Tobagi, "Analysis of a two-hop centralized packet radio network—part I: Slotted ALOHA," *IEEE Trans. Commun.*, vol. COM-28, no. 2, pp. 196–207, Feb 1980.

[6] ——, "Analysis of a two-hop centralized packet radio network—part II: Carrier sense multiple access," *IEEE Trans. Commun.*, vol. COM-28, no. 2, pp. 208–216, Feb 1980.

[7] R. R. Boorstyn, A. Kershenbaum, B. Maglaris, and V. Sahin, "Throughput analysis in multihop CSMA packet radio networks," *IEEE Trans. on Communications*, vol. COM-35, no. 3, pp. 267–274, Mar 1987.

[8] F. A. Tobagi and J. M. Brazio, "Throughput analysis of multihop packet radio network under various channel access schemes," in *Proc. INFOCOM'83*, San Diego, CA, Apr 1983.

[9] T. J. Shepard, "A channel access scheme for large dense packet radio networks," in *Proc. of ACM SIGCOMM*. ACM Press, Aug 1996, pp. 219–230.

[10] H. Chhaya and S. Gupta, "Performance modeling of asynchronous data transfer methods of IEEE 802.11 MAC protocol," *Wireless Networks*, vol. 3, pp. 217–234, 1997.

[11] Y. Wang and J. J. Garcia-Luna-Aceves, "Performance of collision avoidance protocols in single-channel ad hoc networks," in *Proc. of 10th IEEE International Conference on Network Protocols (ICNP)*, Paris, France, Nov 2002.

[12] L. Wu and P. Varshney, "Performance analysis of CSMA and BTMA protocols in multihop networks (I). single channel case," *Information Sciences, Elsevier Sciences Inc.*, vol. 120, pp. 159–177, 1999.

[13] S. Das, C. Perkins, and E. Royer, "Performance Comparison of Two On-demand Routing Protocols for Ad Hoc Networks," in *Proc. IEEE Conference on Computer Communications (INFOCOM)*, Tel Aviv, Israel, March 2000, pp. 3–12.

[14] S. R. Das, C. E. Perkins, E. M. Royer, and M. K. Marina, "Performance comparison of two on-demand routing protocols for ad hoc networks," in *IEEE Personal Communications Magazine, special issue on Mobile Ad Hoc Networks*, Feb 2001.

[15] E. Royer, S. Lee, and C. Perkins, "The Effects of MAC Protocols on Ad hoc Network Communications," in *Proc. IEEE Wireless Communications and Networking Conference(WCNC)*, Chicago, IL, September 2000.

[16] C. Barrett, M. Drozda, A. Marathe, and M. Marathe, "Characterizing the Interaction between Routing and MAC Protocols in Ad-Hoc Networks," in *Proceedings of the ACM International Symposium on Mobile Ad Hoc Networking and Computing (Mobihoc)*, Lausanne, Switzerland, June 2003, pp. 92–103.

[17] F. Bai, N. Sadagopan, and A. Helmy, "IMPORTANT: A framework to systematically analyze the Impact of Mobility on Performance of RouTing protocols for Ad Hoc Networks," in *Proc. IEEE INFOCOM*, San Francisco, CA, USA, April 2003, pp. 825–835.

[18] K. K. Vadde and V. R. Syrotiuk, "Factor Interaction on Service Delivery in Mobile Ad Hoc Networks," *IEEE Journal on Selected Areas in Communications*, pp. 1335–1346, 2004.

[19] K. K. Vadde, V. R. Syrotiuk, and D. C. Montgomery, "Optimizing Protocol Interaction using Response Surface Methodology," *IEEE Transactions on Mobile Computing*, vol. 5, pp. 627–639, 2006.

[20] D. Tse and S. Hanly, "Linear multiuser receivers: Effective interference, effective bandwidth and user capacity," *IEEE Trans. Information Theory*, vol. 45, no. 2, pp. 641–657, Mar 1999.

[21] M. M. Carvalho and J. J. Garcia-Luna-Aceves, "A Scalable Model for Channel Access Protocols in Multihop Ad Hoc Networks," in *Proc. ACM Mobicom*, Philadelphia, USA, Sep 2004.

[22] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535–547, March 2000.

[23] Z. Ye, S. V. Krishnamurthy, and S. K. Tripathi, "A Framework for Reliable Routing in Mobile Ad Hoc Networks," in *Proceedings of the IEEE INFOCOM*, 2003, pp. 270–280.

[24] M. Marina and S. Das, "On-demand Multipath Distance Vector Routing in Ad Hoc Networks," in *Proceedings of IEEE International Conference on Network Protocols (ICNP)*, 2001, pp. 14–23.

[25] A. Nasipuri, R. Castaeda, and S. R. Das, "Performance of Multipath Routing for On-demand Protocols in Mobile Ad Hoc Networks," *Mob. Netw. Appl.*, vol. 6, no. 4, pp. 339–349, 2001.

[26] S. Lee and M. Gerla, "Split Multipath Routing with Maximally Disjoint Paths in Ad Hoc Networks," in *Proceedings of the IEEE ICC*, 2001, pp. 3201–3205.

[27] S. Biswas and R. Morris, "ExOR: Opportunistic Multi-hop Routing for Wireless Networks," in *Proc. ACM SIGCOMM*, 2005.

[28] S. Chachulski, M. Jennings, S. Katti, and D. Katabi, "Trading structure for randomness in wireless opportunistic routing," in *Proc. ACM SIGCOMM*, 2007.

[29] L. Bao, "MALS: Multiple Access Scheduling Based on Latin Squares," in *IEEE MILCOM 2004*, October 31-November 3, 2004.

[30] X. Wang and J. J. Garcia-Luna-Aceves, "Performance Modeling of MAC and Routing Interactions in Multi-hop Wireless Networks," in *Technical reports, Computer Engineering Department, University of California, Santa Cruz*, 2009.