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

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Abstract—We proposed an analytical model to study the interplay between medium access control (MAC) and packet forwarding disciplines in multihop wireless networks. The model jointly considers the channel access procedure and the active portions of the topology, which is determined by 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 multihop 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 multihop 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.

Index Terms—Medium access control, contention-based MAC, schedule-based MAC, multipath, opportunistic forwarding.

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1 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.

One important limitation about current wireless network protocol design is that the MAC or routing protocol is treated *in isolation*. Usually one MAC or routing algorithm is evaluated under the setting of specific routing (MAC) protocols. The results obtained through this method are *unilateral* and even *misleading*, e.g., can one MAC or routing algorithm still performs well when combining with a different kind of routing (MAC) protocols? Why there is a huge performance difference for different MAC and routing protocol combinations? Considering the entire protocol stack works as a single dynamic system, we cannot answer the above questions without investigating the interplay between MAC and routing. Actually the interaction between MAC layer and network layer is of paramount importance to the performance of wireless networks, as Section 2 indicates. Very little has been done to model it analytically 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 (PHY) layer. Section 3 discusses the interactions between different protocol layers and the rationale for our model framework. Section 4 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 to channel access in multihop wireless networks 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, Sections 5 and 6 apply 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 multihop wireless networks.

Section 7 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 multihop networks of 50 and 100 nodes display a very good correlation with the results obtained through our analytical model. We also analyzed how different packet forwarding disciplines

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interact with different channel access schemes to influence the system performance.

2 RELATED WORK

In this section, we first briefly review the joint MAC and routing protocol design in wireless networks; then, we introduce the existing performance modeling work of MAC and routing interaction.

2.1 Joint MAC and Routing Protocol Design in Wireless Networks

With the emergence of multichannel multiradio networks, more and more research work on joint routing and MAC protocol design (e.g., scheduling or channel assignment) is proposed to utilize the frequency diversity of the wireless networks. Raniwala and chker Chiueh [3] propose a centralized channel assignment and routing algorithm to obtain a static frequency assignment. Kyasanur and Vaidya [4] propose an interface-assignment strategy where the number of available interfaces is less than the number of available channels. It fixes a channel on one radio and switches channels on other radios. Nodes can communicate with each other through the fixed common radio without requiring specialized coordination algorithms.

Kodialam and Nandagopal [5] consider the problem of jointly routing and scheduling transmissions to achieve a given rate vector. They use a simple interference model, which is derived from the CDMA-based multihop networks to map the scheduling problem to edge coloring problem. They have proven that their solution is within $\frac{2}{3}$ of the optimal solution. Zhang et al. [6] formalize the problem for joint routing and channel switching in wireless mesh networks and use column generation method to solve the problem. Alicherry et al. [7] formulate the joint frequency assignment and routing problem for infrastructure wireless mesh networks. They aim to maximize the bandwidth allocated to each traffic aggregation point subjected to fairness constraint and propose a constant approximation algorithm for this NP-hard problem. Kodialam and Nandagopal [8] develop a network model that characterizes the channel, radio, and interference constraint in a fixed broadband wireless network, which provides necessary and sufficient conditions for a feasible frequency assignment and schedule. Meng et al. [9] formulate the joint routing and channel assignment problem based on radio and radio-to-radio link. They introduce a *scheduling graph* and derive a sufficient condition for the feasibility problem of time fraction.

Tam and Tseng [10] propose a joint multichannel and multipath control protocol (JMM). JMM coordinates channel usage among slots using a receiver-based channel assignment and schedules transmissions along dual paths. JMM uses a routing metric which explicitly accounts for the disjointness between paths and interference among links to select two maximally disjoint paths. Wu et al. [11] propose a channel cost metric (CCM) which reflects the interference cost and channel diversities. Based on CCM, a distributed joint frequency assignment and routing protocol is proposed.

2.2 Performance Modeling of MAC and Packet Forwarding Interaction

A significant amount of work (e.g., [12], [13], [14], [15], [16], [17], [18], [19], [20], [21]) 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. [22], [23] use a simulation model to show that the interplay between routing and MAC protocols affects the performance significantly in the context of Ad hoc On-Demand Distance Vector Routing (AODV) and Dynamic Source Routing (DSR). Royer et al. [24] 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 (e.g., the MAC layer feedback of unreachable next hops).

Barrett et al. [25] conducted a comprehensive simulation study to characterize the interaction between MAC and routing protocols, node speed, and data rates in mobile ad hoc networks (MANET). 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. [26] 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 mobile ad hoc networks routing protocols, the effect of mobility on these building blocks and how they influence the protocol as a whole.

Vadde and Syrotiuk [27] studied the impact of quality of service (QoS) architectures, routing protocols, and MAC protocols on service delivery in MANETs, using interaction graphs to visualize the two-way interactions between factors. Vadde and Syrotiuk [28] 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 multihop 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. In contrast to the previous modeling work that treats MAC and network layer

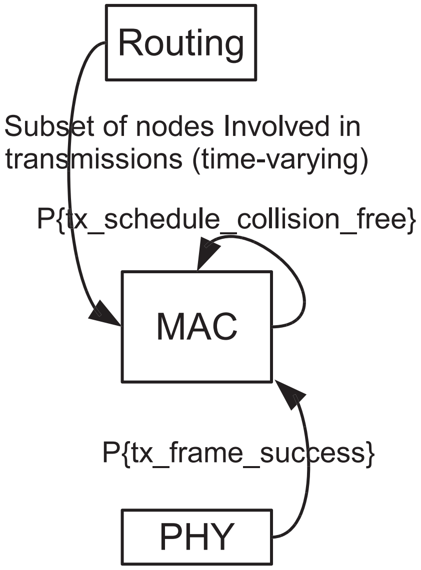


Fig. 1. Protocol interaction.

independently, we incorporate factors from different layers into one framework to capture the dynamic protocol interactions. More specifically, we focus on the impacts of the active topology change (determined by different packet forwarding rules) on the channel access procedure. Instead of simply comparing the performance between different protocol combinations, we try to illustrate how protocol interactions change the important performance factors that in turn determine the system performance. Through this approach, we detailed analyzed how different packet forwarding rules (multipath or multicopy forwarding) influence the underlying channel access schemes (contention-based or schedule-based channel access). In practice, it is not meaningful to study a single MAC or routing protocol in isolation. The proposed model framework could provide more accurate evaluation about system performance.

3 PROTOCOL INTERACTIONS

In this section, we address the interactions between protocol stacks and the classification of different feedback information.

As Fig. 1 shows, 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: 1) Feedback information that does not depend on the activity of other nodes (e.g., whether a node has data packets to send); and 2) 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 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., hundreds of 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).

4 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 are more than one nodes transmit to the same receiver simultaneously, the whole frame transmission is a failure (we assume that all partial overlapping transmissions will fail). Table 1 lists the notations used throughout this paper.

4.1 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 (we just consider the nodes on the selected routing path as interfering nodes because if a node is unselected, it is not involved in any routing activities or data packets transmissions. Given the MAC layer does not receive any frames from upper layers, it will not be involved in channel access procedure even though the node is in the interference range).

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 [29]

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

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

TABLE 1
Symbol Table

P_k^r	received signal power at node r for a signal transmitted by node k	V	the finite set nodes spanning the network under consideration
V_r	subset of nodes that are in the reception range of node r	V_r'	subset of nodes that are on the selected routing path
$SINR_i^r(t)$	signal-to-interference-plus-noise density ratio for a signal transmitted by node i and received at node r	σ_r^2	background or thermal noise power at the front end of the receiver r
$\chi_j(t)$	an on/off indicator reflecting MAC layer transmission scheduling(contention) results	$\{c_{ik}^r\}$	set of combinations of active transmitting nodes in V_r'
$\gamma(c_{i0}^r)$	SINR at node r for a bit transmitted by i when none of r's interferers transmits	L_i	spreading gain (or bandwidth expansion factor) of the spread-spectrum system
K	length of the frame in bits	$P_b(\gamma)$	bit-error probability for a certain SINR level γ
$f(c_{i0}^r)$	probability of successful frame reception	q	probability that a transmitted packet does not collide
τ_i	steady-state scheduling rate	$h_i(\cdot)$	a time-invariant function relating the successful transmission probability q_i
$\mathcal{C}_i^r$	random variable that indicates the occurrence of a specific combination c_{ik}^r of interferers	S_i	average MAC layer one-hop throughput for any node i
$\overline{T_i}$	average service time of node i	S_E	end-to-end throughput
h_j	hop length of path j	$\overline{T}$	average service time
$\overline{T}_B$	average backoff time	$\overline{T}_S$	average time to successfully transmit a packet at the end of the backoff operation
p_s^i	probability that a transmission is successful	p_i^i	probability that the channel is idle
p_c^i	probability that a collision occurs	p_{suc}^i	conditional probability that some node in V_r' transmits successfully given at least one node in S_i attempted to transmits
ϕ_i	probability that the transmission schedule for node i is collision-free	$P_{success\_info}$	probability that the topology information exchange is successful
t_{data}	data slot length	t_{signal}	signal slot length
N_{data}	number of data slots	N_{signal}	number of signal slots
N_2^i	number of neighbors within two hops of i		

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

$\chi_j(t)$ 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 to the probability that no neighbor of the receiver transmits and the packet is received correctly (we assume that all partial overlapping transmissions will fail). 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 and Garcia-Luna-Aceves [30] and Bianchi's model [31]. 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 a 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 (the key point of the model framework is to find the correlation between the steady-state MAC layer scheduling rate (τ_i) and the successful transmission probability q_i, the detailed protocol operations like different retransmission policies will influence how we derive the $h_i(\cdot)$, but it will not change the model framework).

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':

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

Since the probability of successful reception under simultaneous transmissions is so small compared with the no collisions case, we approximate that part as zero in the numerical calculation (the capture effect is ignored). 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 (8)

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

Since the probability of successful frame reception under simultaneous transmissions is so small compared with the no collisions case, we approximate that part as zero in the numerical calculation (the capture effect is ignored). After the linear approximation using the Taylor series expansion (justified in [30]), we have

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

From (12),

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

If we assume $a \ll 1$ (a actually reflects the joint probability that a node successfully gained channel access and the transmission did not experience any collisions. Since both probability are small values, it is reasonable to assume that a $\ll 1$), 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 (12) and (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.

4.2 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 (15).

4.3 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 [32], which are paths to a destination in which a node appears in at most one path.
2. Link-disjoint paths [33], [34], 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 [35], which are paths to a destination that have the minimum cost among 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: 1) it has the shortest distance among all the unselected paths; 2) 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 will select the path with the smaller IP address. We continue this process 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* [30] to take into account the effect of routing factors. As indicated in (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: 1) The received interference signal power at the receiver is above the carrier sensing threshold, as indicated in [30]; and 2) it is on at least one of the routing paths.

4.4 Interaction with Packet Forwarding Disciplines

Once routing paths are formed, nodes use different forwarding rules to select their successors. Opportunistic routing protocols [36], [37] 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 toward a destination with a probability p_f.

As in Section 4.3, 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 $h_i(.)$.

5 MODELING CONTENTION-BASED MAC: 802.11 DCF

In this Section, we extend the prior model proposed by Carvalho and Garcia-Luna-Aceves [30] and Bianchi's model [31] to study the interactions between 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 [30]

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

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., $W_{\max} = 2^m W_{\min}$.

Equation (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 could derive a first order approximation for it using Taylor series expansion and express τ_i in terms of q_i

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

when we consider all nodes in the topology, can be rewritten in the 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.,

$$\begin{aligned} p_{suc}^i &= \frac{\sum_{k \in S_i} P\{k \text{ succeed} \mid k \text{ transmits}\} P\{k \text{ transmits}\}}{p_{tr}^i} \\ &= \frac{\sum_{k \in S_i} q_k \tau_k}{p_{tr}^i}. \end{aligned} \tag{20}$$

Then, according to Bianchi's model [31], the probability that a transmission is successful is $p_s^i = p_{tr}^i p_{suc}^i$; the probability that the channel is idle is $p_i^i = 1 - p_{tr}^i$, and the probability that a collision occurs is $p_c^i = p_{tr}^i(1 - p_{suc}^i)$. We can further derive $\overline{T}_B$ and $\overline{T}_S$ using p_s^i, p_i^i, and p_c^i according to the methods described in [31].

6 MODELING SCHEDULE-BASED MAC: NAMA

We choose NAMA [1], [38] as an example of schedule-based MAC schemes, because it completely eliminates the communication overheads of building the dynamic channel access schedule, except for collecting two-hop neighbor information, which is minimal 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 its two-hop neighbors. If a node has the highest priority, the node can access the channel within the corresponding time slot, while its 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:

$$\phi_i = P_{\{no\_conflicts|success\_info\}} P_{success\_info}, \tag{21}$$

where $P_{success\_info}$ is the probability that the topology 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 the unsuccessful information exchange leads to transmission collisions.

Then,

$$\tau_i = \phi_i q_i. \tag{22}$$

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

$$T_f = N_{signal} t_{signal} + N_{data} t_{data}, \tag{23}$$

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 (6)

$$P_{success\_info} = f(c_{i0}^r) P\{\text{no neighbor transmits}\}. \tag{24}$$

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

TABLE 2
Simulation Parameters

802.11a 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				

$$P\{\text{no neighbor transmits}\} = \left(1 - \frac{1}{N_{signal}}\right)^{N_2^i - 1}, \tag{25}$$

where N_2^i is the number of neighbors within two hops of i.

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

$$p_s^i = \frac{1}{N_2^i}. \tag{26}$$

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 topology information

$$P_{\{no\_conflicts|success\_info\}} = 1, \tag{27}$$

$$\phi_i = p_s^i P_{success\_info}. \tag{28}$$

From (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

$$\overline{T} = \frac{T_f}{\lceil \tau_i N_{data} \rceil}. \tag{29}$$

7 MODEL VALIDATION

7.1 Simulation Settings

We compare the numerical results with the simulation results obtained from Qualnet 3.9 [2]. The detailed simulation settings can be found in Table 2 [30]. The packet length used is 1,500 bytes. The duration of the simulation is 100 seconds. For the system throughput results, the simulations are repeated with 10 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 multihop CBR flows and vary the number of CBR flows to investigate the influence of packet forwarding methods.

7.2 Interaction between Multipath Routing and MAC

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

7.2.1 *802.11 DCF*

To demonstrate the model accuracy and provide some insights on system performance difference, we first examine the per-node throughput of 802.11 DCF, as Fig. 2 shows. Comparing Figs. 2a and 2b, 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 (1-21), the larger the contention neighbor sets 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 3 shows.

7.2.2 *NAMA*

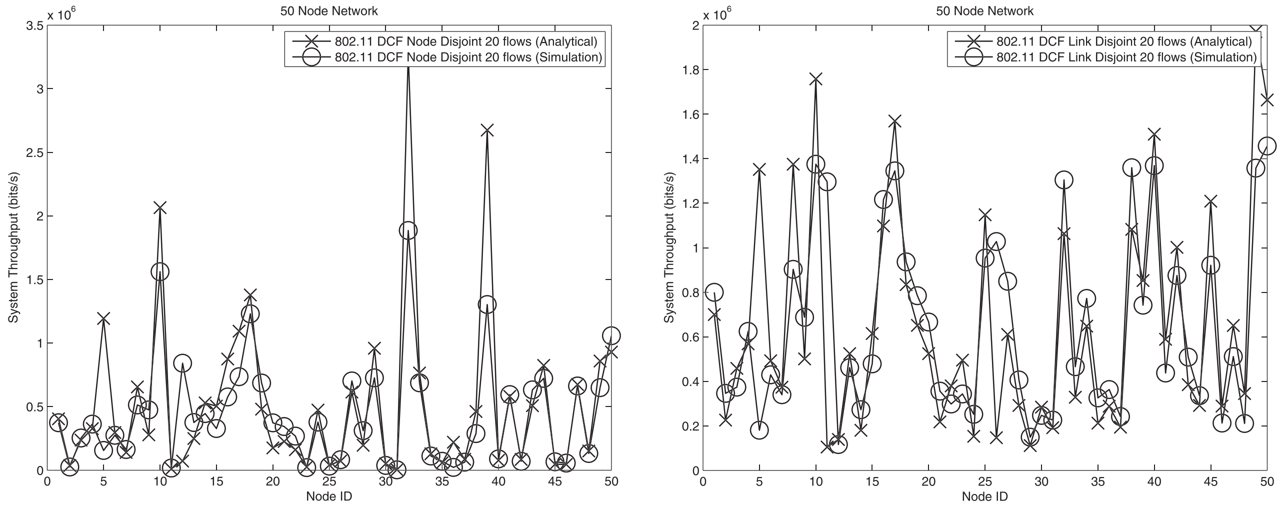
In contrast to contention-based MAC protocols, when a schedule-based MAC interacts with different multipath packet forwarding disciplines, there is no significant difference between node-disjoint routing and link-disjoint routing. This is shown in Fig. 3 and Table 4.

Revisiting the modeling process of the schedule-based MAC (21), its performance is mainly dependent on two factors: 1) The probability that the topology information exchange is successful, and 2) 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 MACs 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.

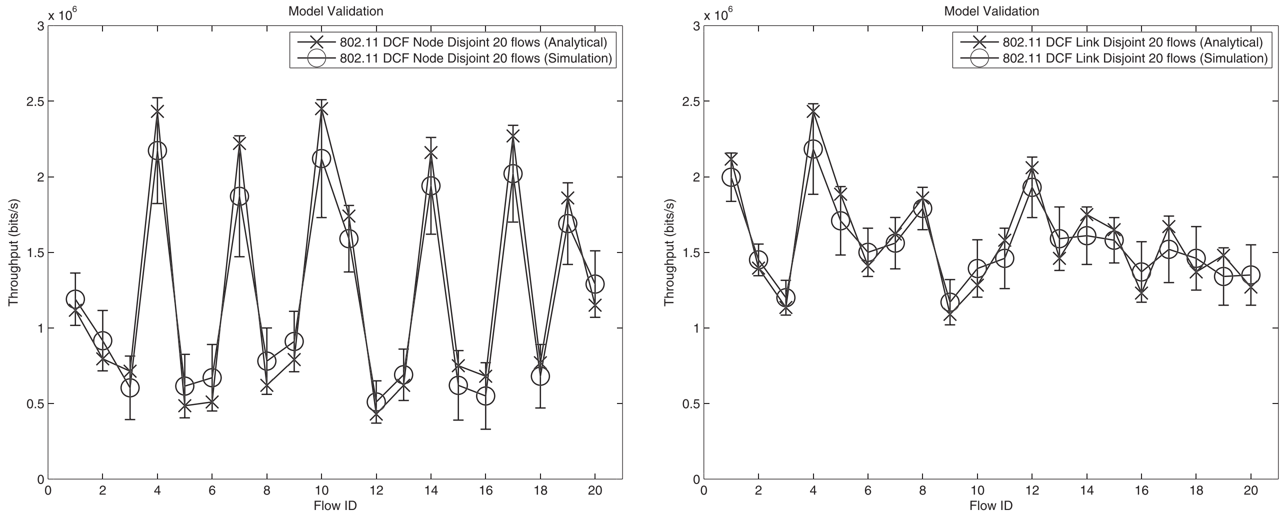
7.2.3 *Model Accuracy*

In order 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 error prediction distribution for each simulation experiment. As Fig. 4 shows, we find that the percentage of prediction error is within 20 percent in about 90 percent of the nodes and within 10 percent in about 80 percent of the



(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. 2. Model validation: 802.11 DCF.

nodes, showing how close our analytical model is in predicting the results obtained in simulations (to the best of our knowledge, the discrepancy between the simulation results and numerical results mainly comes from the inaccuracy of the physical-layer interference estimation. Similar to most of the analytical modeling work, we need to define an interference (reception) range to get V_r. All transmissions outside the interference range are not considered when calculating $f(c^r_{i0})$ and q_i, while Qualnet simulator calculates the SINR based on the aggregate interference, which is more accurate. The discrepancy introduced by the this factor varies according to the topology and traffic patterns).

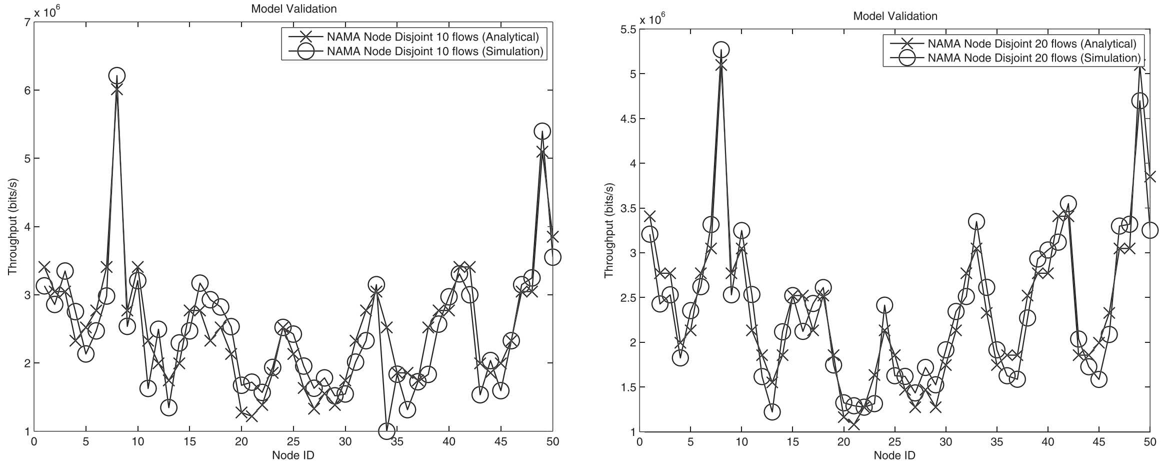
7.3 Interaction between Opportunistic Forwarding and MAC

We now examine the impact of packet forwarding rules on different MAC protocols. For opportunistic forwarding, we

TABLE 3
802.11 DCF System Throughput with Different Multipath Packet Forwarding

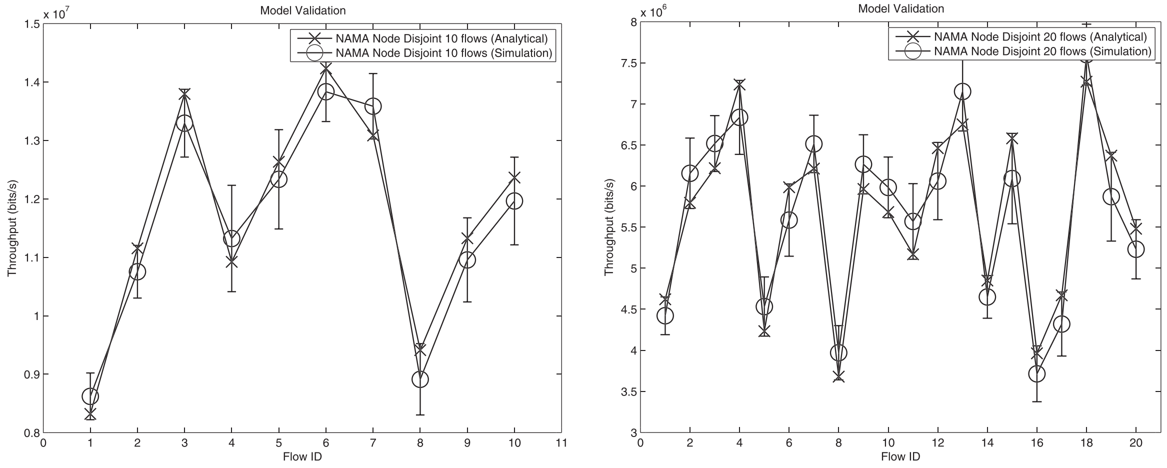
50 nodes	Node-disjoint (analytical) (Mb/s)	Node-disjoint (simulation) (Mb/s)	Link-disjoint (analytical) (Mb/s)	Link-disjoint (simulation) (Mb/s)
10 flows	32.12	28.24	32.55	33.17
20 flows	29.97	28.13	32.65	30.26
30 flows	25.19	23.37	29.99	27.45

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



(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. 3. Model validation: NAMA.

vary different p_f values. As Tables 5, 6, 7, and 8 show, multiple-copy forwarding degrades system throughput while opportunistic forwarding could improve system throughput to some extent.

7.3.1 802.11 DCF

The system throughput comparisons of 802.11 DCF under different packet forwarding rules are shown in Tables 5 and 6. We observe that, when combined with 802.11 DCF, opportunistic forwarding could enhance the system throughput for some p_f.

7.3.2 NAMA

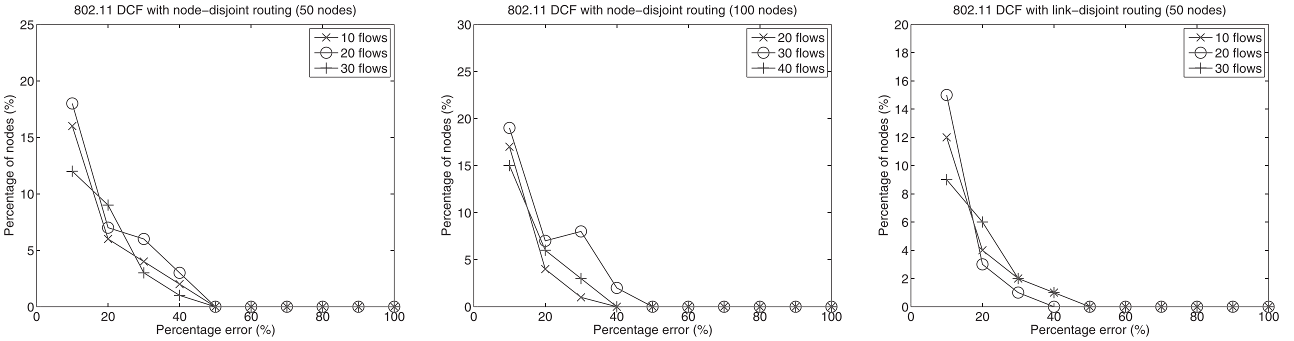
The system throughput results for NAMA using different packet forwarding rules are shown in Tables 7 and 8. We observe that, in contrast to the results shown in Table 5, when combining NAMA with opportunistic forwarding, the improvement of system throughput is quite minor.

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

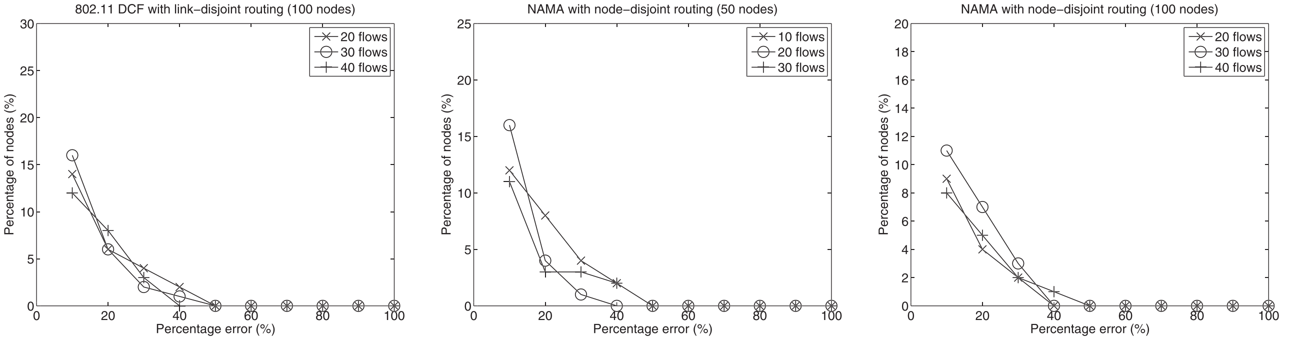
TABLE 4
NAMA System Throughput with Different Multipath Packet Forwarding

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

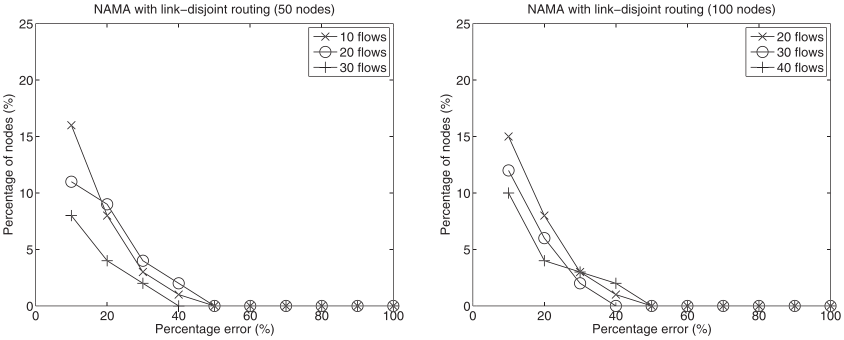
100 nodes	Node-disjoint (analytical)	Node-disjoint (simulation)	Link-disjoint (analytical)	Link-disjoint (simulation)
20 flows	351.80	341.23	323.07	337.15
30 flows	320.94	313.42	314.85	316.38
40 flows	307.59	309.78	301.97	306.42



(a) 802.11 DCF with node-disjoint routing (50 Nodes) (b) 802.11 DCF with node-disjoint routing (100 Nodes) (c) 802.11 DCF with link-disjoint routing (50 Nodes)



(d) 802.11 DCF with link-disjoint routing (100 Nodes) (e) NAMA with node-disjoint routing (50 Nodes) (f) NAMA with node-disjoint routing (100 Nodes)



(g) NAMA with link-disjoint routing (50 Nodes) (h) NAMA with link-disjoint routing (100 Nodes)

Fig. 4. Model prediction error distribution.

duplicate packets. This is at the cost of consuming more system resources, which is the major reason that single-copy forwarding always outperforms multicopy forwarding in terms of throughput. Second, one key aspect of opportunistic forwarding is that the node that forward 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

TABLE 5
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 6
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 7
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 8
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

increases the robustness of the end-to-end transmissions and could accommodate channel fluctuations. However, it is more 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 7 shows. Given that most opportunistic routing schemes have been evaluated over contention-based MAC (802.11 DCF or its extensions) [36], [37], the results obtained in this paper motivate us to rethink how to leverage opportunistic forwarding using generic MAC protocols.

From Tables 6 and 8, 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.

8 Conclusion and Future Work

We introduced a novel analytical model to study the interactions of MAC and packet forwarding schemes in multihop 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.

In this paper, we only consider the case that routing paths have already been established, further analysis about the protocol interactions at different stages of routing protocols is needed. We also observe the opportunistic forwarding principles have different performance when combined with different MAC protocols, how to design a routing protocol that could deliver good performance across different MAC protocols is another problem to solve.

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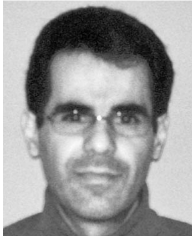

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