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# A Unified Analysis of Routing Protocols in MANETs

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**Abstract**—This paper presents a mathematical framework for the evaluation of the performance of proactive and reactive routing protocols in mobile ad hoc networks (MANETs). This unified framework provides a parametric view of protocol performance, which in turn provides a deeper insight into protocol operations and reveals the compounding and interacting effects of protocol logic and network parameters. The parametric model comes from a combinatorial model, where the routing logic is synthesized along with the characterization of MAC performance. Each wireless node is seen independently as a two-customer queue without priority, where the two types of customers are unicast and broadcast packets. The model captures the essential behavior and scalability limits in network size of both classes of routing protocols, and provides valuable guidance on the performance of reactive or proactive routing protocols under various network configurations and mobility conditions. The analytical results obtained with the proposed model are in close agreement with simulation results obtained from discrete-event *Qualnet* simulations.

**Index Terms**—MANETs, proactive/preactive routing, packet delivery ratio, unicast capacity, performance analysis.

## I. INTRODUCTION

Mobility brings fundamental challenges to the design of routing protocols in mobile ad hoc networks (MANETs). The mobility of nodes implies that the routing protocols of MANETs have to cope with frequent topology changes while attempting to produce correct routing tables. To accomplish this, two types of routing protocols have been proposed: proactive routing and reactive (or on-demand) routing.

Proactive routing protocols provide fast response to topology changes by continuously monitoring topology changes

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and disseminating the related information as needed over the network. However, the price paid for this rapid response to topology changes is the increase in signaling overhead, and this can lead to smaller packet-delivery ratios and longer delays when topology changes increase. In the worst case, “broadcast-storms” [1] can result in congesting the entire network. Reactive routing protocols operate on a need to have basis, and can, in principle, reduce the signaling overhead. However, the long setup time in route discovery and slow response to route changes can offset the benefits derived from on-demand signaling and lead to inferior performance.

Given these striking differences between proactive and on-demand routing in MANETs, a basic question to ask is whether one routing protocol always performs better than the other. Extensive simulations have already given the answer: both of routing algorithms exhibit advantageous and inferior performance to the other one depending on different network configurations, particularly with respect to different node mobility, node density and traffic load.

Given that proactive and reactive routing schemes for MANETs have relative advantages and disadvantages, comparing the two is important. Significant work (e.g., [2]–[5]) has been conducted to evaluate and compare these protocols under network profiles of various mobility and traffic configurations. Such performance comparisons have been mostly conducted via discrete-event simulations. Simulation-based studies of routing schemes are a powerful tool to gain insight on their performance for specific choices of network parameters. However, it is difficult to draw conclusions involving multidimensional parameter spaces, because running several simulation experiments for many combinations of network parameters is impractical. Few if any analytical studies have been pursued on this topic, and prior analytical work has been mostly restricted to the analysis or comparison of routing control on routing metric overhead [6]–[8], information theoretic aspects [9], [10] or multipath routing protocols [11], [12]. Furthermore, these works do not evaluate the effects of signaling overhead on unicast capacity at nodes, and none reveals the underlying connection between protocol performance and network parameters. Hence, the following two questions have remained open:

- Does there exist a unified analytical framework, simplified but able to provide the characterization of essential behaviors of routing protocols?
- If there is one such framework, can it also provide network scalability?

This paper provides a unified analytical framework that pa-

parameterizes and quantitatively evaluates the performance of routing protocols from a joint characterization of the routing logic and MAC layer. The solution emerges from a combinatorial model that synthesizes the evaluation of both the routing logic and the operation of the MAC layer, with each of them being parameterized individually.

The MAC layer at nodes is as well as simplified as a two-customer queuing model, where the packet loss probability and delay at nodes can be effectively computed. When analyzing the performance of the MAC layer, we consider the cases of a scheduled MAC (TDMA) and a contention-based MAC (802.11 DCF MAC). In the combinatorial model, the computed metrics are synthesized along with the routing logic to produce quantitative measures of the routing protocols in terms of end-to-end packet loss probability and delay.

It is important to note that this work does not attempt to model or compare between specific proactive and reactive routing protocols. Rather, the intent is to capture the essential behavior and scalability limits in the network size of both classes of protocols by quantifying their performance within a unified framework. The simulation results in this paper are not intended to provide an exact match with our analysis; they are provided only as a supporting evidence for the conclusions regarding to protocol behaviors observed in literature. With the aid of simulations, we show that the analytic results agree with the simulation findings.

We model each wireless node as a two-customer queue without priority, where the two kinds of customers are unicast and broadcast packets. By analyzing the service time and waiting time in queue for any unicast packet, we derive the transmission delay time for any link; by summing up the transmission delay time for each link of any routing path, we derive the end-to-end delivery delay.

The paper is organized as follows. Section II presents related work in the modeling of routing protocols. Section III presents the mobility model, traffic model and simplified models of routing algorithms used in the analysis in Section IV. Section V characterizes the performance of the MAC layer and provides performance metrics in evaluating protocol performance. Section VI compares our analytical results against Qualnet simulations based on scenarios on various traffic loads, mobility and node density configurations. The results illustrate the correctness of our analytical framework, which captures the essential behaviors of protocols and is capable of pinpointing the effect of various parameters analytically. Section VII concludes this paper.

## II. RELATED WORK

Parameterizing and comparing the performance of routing protocols analytically is a very complex problem. Consequently, the characterization and comparison of routing protocols have been limited to simulation-based approaches [2]–[5], [13]–[16], under various configurations. The performance evaluation metrics used in these simulations or experimental-based approaches include packet delivery ratio, delay and throughput. Network configurations vary on traffic pattern, mobility and network density.

Certain analytical studies on routing overhead has been carried out. Viennot *et al.* [6] proposed parametric models

for proactive and reactive protocols to evaluate the individual routing control overhead. Zhou and Abouzeid [7] presented an analytical view of routing overhead for reactive protocols, assuming a static Manhattan-grid network and studied the scalability of reactive protocols. These studies concentrate on the impact of traffic patterns and they also provide [8] a mathematical and simulation-based framework for quantifying the overhead of reactive routing protocols.

Zhou and Abouzeid extended their analytical studies to information theoretic techniques to derive analytic expressions for specific metrics, such as control message routing overhead and memory size requirement [9] where entropy is utilized to derive bounds for these metrics. They have made fundamental contributions [10] toward a rigorous modeling, design and performance comparisons of protocols by deriving lower bounds on the routing protocol.

Tsirigos *et al.* [11], [12] studied multipath routing protocols with the aim of increasing packet delivery ratio in inherently unreliable networks and developed an analytical framework for evaluating them. Their work took mobility and topology changes into considerations.

Our work has been inspired by research work in [17]–[20] which analyzes and evaluates the performance of routing protocols by constructing mathematical models of the routing operations.

Yang *et al.* [17] set up a mathematical model that imitates the operation of proactive routing and is utilized to optimize the operation of routing protocols in order to strike a balance between protocol overhead and accuracy. However, this work is specific for proactive protocols operating under certain conditions.

Lebedev [18] showed an analytical tool for both proactive and reactive protocols and proposed a model to study the operation of two classic reactive (Ad-hoc reactive Distance Vector Routing (AODV) [21]) and proactive (Optimized Link State Routing (OLSR) [22]) protocols in the presence of faulty links. However, this work does not cover other aspects of network parameters on the performance of routing protocols.

Nogales [19] models routing protocols with the consideration of the behavior of connections at the link layer and MAC protocol. However, that model is greatly simplified when modeling the packet routing and scheduling process and does not take into consideration traffic load and the topology of the network.

Jacquet and Laouti [20] compare proactive and reactive routing protocols performance by proposing probability-based models. However, their models focus on calculating specific performance metric values, rather than evaluating the general operations of these routing protocols. Their study is based on random graph models that are simplified and idealized, such that mac and link layer failure effects are not taken into consideration.

## III. NETWORK MODEL

### A. Mobility Model

Nodes are mobile and initially they are distributed equally over the network. The movement of each node is independent and unrestricted, i.e., the trajectories of nodes can lead to

anywhere in the network. For node  $i \in V = \{1, 2, \dots, N\}$ , let  $\{T_i(t), t \geq 0\}$  be the random process representing its trajectory and take values in  $Y$ , where  $Y$  denotes the domain across which the given node moves. To simplify the model, we make the following assumption on the trajectory processes.

*Assumption 1: [Stationarity]* Each of the trajectory processes ( $T_i(t)$ ) is stationary, i.e., the spatial node distribution reaches its steady-state distribution irrespective of the initial location. The  $N$  trajectory processes are *jointly stationary*, i.e., the whole network eventually reaches the same steady state from any initial node placements, within which the statistical spatial nodes' distribution of the network remains the same over time.

The above assumption is quite fundamental in the sense that it lays the foundation for the modeling of node movement. Most existing models, (e.g., random direction mobility models [23], random waypoint mobility models [24], [25] and random trip mobility model [26]) clearly satisfy our assumption. In other words, our assumption ensures that, on the long run, the network converges to its steady state and the stationary spatial nodes' distribution can be used in the performance analysis of the network.

### B. Traffic Model

We consider a new traffic flow or simply a new session as one that is associated by the arrival of a new application-level session request at a node  $i$  with some destination  $j$ ,  $j \neq i$ , in the network. Traffic flows are randomly generated with uniformly distributed sources and destinations. Long-lived traffic flows are assumed in order to investigate protocol performance under the steady state of nodes mobility and traffic distributions. Short-lived traffic flows, reflecting transient behaviors, are beyond the scope of this paper. Furthermore, well-connected networks are assumed, i.e., if an existing path for any traffic session is broken, there is always an alternative path (with high probability) available to support continuing operations of the traffic flow.<sup>1</sup>

### C. Neighbor Sensing

Neighbor sensing protocols, such as periodic broadcasts of HELLO messages, are effective approaches used in routing protocols (both proactive and reactive) to detect the availability of links between neighbor nodes. New links are detected when HELLO messages are received from nodes not included in the neighbor list. Existing links are declared as failed if none of HELLO messages from the neighbor node is received during a certain amount of time window.

### D. Routing Protocols Model

We provide descriptions of generic proactive and reactive routing protocols, which we believe capture the essential behavior of many designs and implementations of existing routing protocols. However, this analysis, and hence the generic protocols below, does not consider any protocol-specific techniques, such as multi-point relay, local repairs and route caching mechanisms.

<sup>1</sup>Note that the alternative path is not necessarily disjoint with the former broken path.

1) *Proactive Routing Protocol:* In proactive routing protocols, every node maintains a list of destinations and updates its routes to them by analyzing periodic topology broadcasts from other nodes. When a packet arrives, the node checks its routing table and forwards the packet accordingly.

Every node monitors its neighboring links and every change in its neighbors results in a topology broadcast packet. That is flooded over the entire network. Other nodes update their routing tables accordingly upon receiving the update packet. In a well-connected network, the same topology broadcast packet could reach nodes multiple times and therefore enjoy a good packet reception probability. In the paper, we assume that every node reliably receives topology packets from other nodes.

2) *Reactive Routing Protocol:* In reactive routing protocols, nodes maintain their routing tables on a needed basis. This implies that when a new traffic session arrives, nodes have to set up the paths between sources and destinations before starting to deliver data packets. The process of path setup is called *route discovery*. Complementarily, another process called *route maintenance* is necessary to find an alternative path if a former path was broken. More specifically:

a) *Route Discovery:* a mechanism initiated by a node  $i$  upon the arrival of a "new traffic session" in order to discover a new path to a node  $j$ . Node  $i$  floods the whole network with route request (RREQ) packets. Upon receiving the RREQ packet, node  $j$  sends out a route reply packet (RREP) along the reverse path to  $i$ . As a result, node  $i$  usually gets a shortest path to node  $j$ .

b) *Route Maintenance:* a mechanism by which a node  $i$  is notified that a link along an active path has broken, such that it can no longer reach the destination node  $j$  through that route. Upon reception of a notification of route failure, node  $i$  can initiate a route discovery again to find a new route for the remaining packets destined to  $j$ .

In reactive routing protocols, each node does not maintain routing tables before a routing task is triggered. They only find a route on demand by flooding the network with RREQs, i.e., before sending data packets sender broadcasts router request and initiates a route discovery process. If a link breakage is detected during packet delivery, a new RREQ is generated. The main disadvantages of such algorithms are high latency time in finding routes and excessive flooding when traffic load is high.

Assume that a successful delivery between source node  $S$  and destination node  $U$  takes  $K$  hops, that at the first step a route discovery is initiated at  $S$  and that after time  $\Delta_0$  source node  $S$  receives a RREP and starts sending data packets. Assume that a link breakage occurs at a relay node  $F$  with probability  $p_i$  and then a new RREQ is generated for  $F$  and that it takes time  $\Delta_i$  to restart delivery. Let us suppose that the transmission delay for any link  $i$  is  $T_i$ . Then the end-to-end delivery delay  $D_p$  between  $S$  and  $U$  can be formulated as  $D_p = \Delta_0 + \sum_{i=1}^K (p_i \Delta_i + T_i)$ .

Compared to the local recovery time in proactive routing protocols, the route discovery time in reactive routing protocols is much larger.

#### IV. UNIFIED FRAMEWORK FOR QUANTIFYING PROTOCOL PERFORMANCE

##### A. Logic Efficiency

We start by looking at the operation of a traffic flow, say from node  $i$  to node  $j$ . Since we are interested in the long-term behavior with steady traffic, the initial traffic and network setup cost are usually small and negligible. The operation of the traffic flow can then be generally classified into two alternating scenarios: data phase and exception phase. During the data phase, the active path has been setup and data packets are delivered from  $i$  to  $j$  along an active route. The exception phase is triggered when a link failure is detected in the active path and an alternative path needs to be discovered. Let  $T_a$  and  $T_e$  be the mean duration of time for the data phase and the exception phase, respectively. And let *logic efficiency*  $\rho_l$  be the ratio between the data phase and the overall time, that is,  $\rho_l = T_a/(T_a + T_e)$ .

Both proactive and reactive protocols share similar data phases, dictated from underlying joint trajectory process. Therefore, one parameter  $T_a$  is used for both protocols. However, the time of the exception phase is dramatically different. Further decomposition of the exception phase reveals that proactive and reactive protocols bear different operating logics. The exception phase  $T_e^p$  in proactive protocols involves the time window  $W_l$ , a protocol parameter for link-failure detection, and the local link repair time  $T_{lr}$  determined by network topology update frequency, i.e.,  $T_e^p = W_l + T_{lr}$ . For reactive protocols, the exception phase  $T_e^o$  involves four steps: (1) link failure detection, denoted by  $W_l$ ; (2) link failure unicasted back to source, by  $T_{lf}$ ; (3) RREQ broadcast flooding, by  $T_{rreq}$ ; and (4) RREP unicasted back to source, by  $T_{rrep}$ . Then, we have  $T_e^o = W_l + T_{lf} + T_{rreq} + T_{rrep}$ . The logic efficiency  $\rho_l^p$  (or  $\rho_l^r$ ) of a proactive protocol (or reactive protocol) can then be evaluated as

$$\begin{aligned}\rho_l^p &= T_a/(T_a + W_l + T_{lr}), \\ \rho_l^r &= T_a/(T_a + W_l + T_{lf} + T_{rreq} + T_{rrep}).\end{aligned}\quad (1)$$

For now, the routing logics can be represented by a tuple of parameters called *logic parameter tuple* (LPT)  $\bar{\theta}_l = \{T_a, W_l, T_{lr}, T_{lf}, T_{rreq}, T_{rrep}\}$ .

##### B. Operation Efficiency

During the data phase, data packets are unicasted along the active path from source to the destination. From a queuing perspective, nodes along the active path form a tandem network of queues. Since every node takes two kinds of traffic: broadcast packets and unicast packets, every node can then be treated as a two-customer queue. To simplify the analysis, we make the following assumptions.

- We assume the nominal packet length  $L$  for both broadcast and unicast packets, while the model can be extended to incorporate various packet length distributions.
- The arrival of broadcast (or unicast) traffic is assumed to be poisson at rate  $\lambda_B$  (or  $\lambda_U$ ). Such a Markovian input assumption can be justified theoretically as the sum of a large number of independent random traffics from the neighboring nodes. Each node is now modeled as a M/G/1 FCFS queue.

- We assume that every queue operates independent of each other. This is a strong hypothesis, because the traffic among nodes may be heavily correlated, especially when data traffic between nodes originates from one same source rather than multiple independent streams. However, in practice, the model still gives a satisfactory approximation, as observed from simulations in [27].

Each node can now be represented by a tuple of parameters termed *MAC parameter tuple* (MPT)  $\bar{\theta}_m = \{\lambda_B, \lambda_U, \bar{S}_B, \bar{S}_U, \nu_B, \nu_U, p_e\}$ , where  $\{\bar{S}_B, \nu_B\}$  (or  $\{\bar{S}_U, \nu_U\}$ ) stand for the mean and variance of service time of broadcast packets (or unicast packets) respectively and  $p_e$  denotes the packet loss probability.

To ensure that protocols operate with correct logics, it is clear that nodes who actually perform the task of delivering packets should be functional. Since nodes are modeled as M/G/1 queues, for queues to be stable and functional, we can infer the scalability constraint [28] as  $E(\lambda_B \bar{S}_B + \lambda_U \bar{S}_U) < 1$ . The left side of the equation, as shown later, is certainly a function of network size  $N$ . Furthermore, a reduced constraint without involving data traffic can be written as,  $E(\lambda_B \bar{S}_B) < 1$ . The maximum stable and functional data traffic can be calculated as  $1 - \lambda_B \bar{S}_B$ . Since  $\bar{S}_U$  implies how efficiently one unicast packet is processed, the *operation efficiency*  $\rho_o$  is thus defined as process efficiency over unicast packets from the whole network as

$$\rho_o = E((1 - \lambda_B \bar{S}_B) \frac{1}{\bar{S}_U}).\quad (2)$$

As indicated in Eq.(2), operation efficiency also indicates the service capacity for unicast packets. Clearly, proactive (or reactive) protocols enjoy their individual operation efficiency  $\rho_o^p$  (or  $\rho_o^r$ ), because they exhibit different MAC performance induced from different  $\bar{\theta}_m$ .

Until now, the overall protocol efficiency  $\rho$  can be computed from both logic and operation efficiency as

$$\rho = \rho_l \times \rho_o.\quad (3)$$

Nevertheless, Eq.(3) is a rather simple model for characterizing protocol performance, leaving out many nuances in protocol behavior. However, such a model certainly captures essential aspects of routing protocols, accounting for behaviors both in data phase and exception phase, and involving both routing logics and MAC performance.

##### C. Characterization of Broadcast Rate

Clearly, a broadcast rate  $\lambda_B$  that reflects routing overhead plays an essential role in determining protocol performance. The generation of flooding packets is directly connected to the stability of the topology. After knowing the stability of topology, such knowledge can be further translated into knowledge of the broadcast rate [29]. As described in the abstract routing protocol model in Section III-D, we simply assume that every topology change triggers one broadcast event.

We know that the topology is comprised of the set of all active links participating in the protocol operation and it usually involves a significant number of active links. Let the set of all active links be denoted by  $A_s(t)$  and  $N_s(t) = |A_s(t)|$

be the number of links in the active set, where  $|\cdot|$  is the cardinality operator and  $t$  is the time index. Note that the topology changes with time  $t$  and due to the ergodicity in the joint trajectory processes, its stationary distribution can be derived from the stationary spatial nodes' distribution with respect to the underlying mobility models [29].

For any topology  $A_s(t)$  and  $N_s(t)$ , if we are concerned only with the breakage of active links in the topology, the distribution of stability of the topology should be the superposition of  $N_s(t)$  i.i.d. random variables all conforming to the distribution of link lifetime  $T_L$ . Resorting to Palm's theorem [30], it can be concluded that the distribution of such a particular topology can also be approximated as exponentially distributed as,  $F_{A_s(t)}(t) \approx \exp(-N_s(t) * t/T_L)$ .

When a network is running in steady-state and the process of topology change is ergodic, it experiences all possible topologies with an associated probability vector derived from the steady-state nodes' distribution. By averaging all possible topologies, we can compute complementary cumulative distribution function (CCDF)  $F(t)$  characterizing the stability of topology [29] as

$$F(t) \approx \exp(-E(N_s(t)) * t/T_L), \quad (4)$$

where  $T_L$  stands for the mean link lifetime.

It should be pointed out that in the above analysis, only the breakage process of existing links is counted while formation process of new links isn't counted. However, in proactive protocols such as the optimized link state routing (OLSR) protocol [31], both the formation and breakage process should be counted, since both of them could trigger protocol events. Luckily, in the long run for a network with a finite number of nodes, the formation and breakage process should be balanced off each other. Then the overall CCDF distribution accounting for both the formation and breakage process is

$$F(t) \approx \exp(2 * -E(N_s(t)) * t/T_L). \quad (5)$$

It is also worth noting that for reactive protocols such as ad hoc on-demand distance vector (AODV) routing [32], only the breakage process triggers the protocol event and the stability of the topology should be evaluated by Eq. (4).

Summarizing our analysis, we can approximate the mean broadcast rate as below,

$$\lambda_B = \begin{cases} E(N_s(t))/T_L, & \text{reactive} \\ 2E(N_s(t))/T_L. & \text{proactive} \end{cases} \quad (6)$$

In reactive protocols, the possible breakage comes from all the path links involved in ongoing traffic sessions; assume that there are  $N_f$  parallel traffic sessions in the network and the average source-destination hop-distance for each session is  $\bar{K}$ , the number of active links  $E(N_s(t))$  can thus be approximated as  $E(N_s(t)) \approx \bar{K} * N_f$ . For proactive protocols,  $E(N_s(t))$  can be approximated as [29]  $E(N_s(t)) \approx C_N^2 * (\pi * R^2 / A_n)$ , where  $R$  is the radius of communication range,  $C_N^2$  is the possible number of bits between source and destination, and  $A_n$  stands for the physical area size of the network.

#### D. Delay Aspect & Packet Loss Probability

The one-hop delay of broadcast packets  $D_B$  or unicast packets  $D_U$  is composed of waiting time in queue for broadcast

packets  $Q_B$  (with mean value  $\bar{Q}_B$ ) or unicast packets  $Q_U$  (with mean value  $\bar{Q}_U$ ) and service time for broadcast packets  $S_B$  or unicast packets  $S_U$ . For the two-customer M/G/1 model without priority,  $Q_B = Q_U$  and then they can be computed respectively as [28]

$$\begin{aligned} D_B &= \bar{S}_B + \bar{Q}_B = \bar{S}_B + \frac{\lambda_B(\bar{S}_B^2 + \mathcal{V}_B) + \lambda_U(\bar{S}_U^2 + \mathcal{V}_U)}{2(1 - \lambda_B\bar{S}_B - \lambda_U\bar{S}_U)} \\ D_U &= \bar{S}_U + \bar{Q}_U = \bar{S}_U + \frac{\lambda_B(\bar{S}_B^2 + \mathcal{V}_B) + \lambda_U(\bar{S}_U^2 + \mathcal{V}_U)}{2(1 - \lambda_B\bar{S}_B - \lambda_U\bar{S}_U)}. \end{aligned} \quad (7)$$

For a particular  $K$ -hop active path, say  $\{N_1 \rightarrow N_2 \rightarrow \dots \rightarrow N_{K+1}\}$ , the end-to-end delay  $D_K(t)$  and the end-to-end packet loss probability  $P_{e,K}(t)$  at such time instance  $t$  can be computed as,

$$\begin{aligned} D_K(t) &= \sum_{\forall i \in \{1, \dots, K\}} D_U^i, \\ P_{e,K}(t) &= 1 - \prod_{\forall i \in \{1, \dots, K\}} (1 - P_e^i). \end{aligned} \quad (8)$$

Since nodes are randomly moving under an ergodic process, the active path could experience all possible source-destination distributions and on the long run, the mean end-to-end delay  $D_p$  can be computed as

$$D_p \approx \bar{K} \times D_U. \quad (9)$$

The end-to-end PDR ( $P_d$ ) representing the successful packet delivery ratio between sources and destinations per traffic is now characterized from the worst-case analysis, which captures the most congested point in the network and can be approximated as

$$\begin{aligned} P_d &= E(1 - P_{e,K}(t)) = E\left(\prod_{\forall i \in \{1, \dots, K\}} (1 - P_e^i)\right) \\ &\approx (1 - P_e)^{\bar{K}}. \end{aligned} \quad (10)$$

#### E. Evaluation of Logic Parameter Tuple

In the logic parameter tuple  $\vec{\theta}_l$ ,  $T_a$  measures the average path lifetime. Assume a significant number of links are involved in a path and  $T_L$  is the mean link lifetime, the path lifetime for a  $K$ -hop path can be approximated as exponential distribution,  $\exp(-Kt/T_L)$  [33]. Then, for a general case  $T_a$  can be approximated as  $T_L/\bar{K}$ .  $T_L$  usually takes the form  $T_L = \Theta(R/V)$  [34] and can be written as  $T_L = c_1 * R/V$ , where  $c_1$  is a constant determined from the underlying mobility model.  $T_{lf}$  is the average time of RREP packets traveling back to the source. Because the path can break at any point in the middle and if assumed uniform distribution of such breakages, it can be computed as  $T_{lf} = \bar{K}/2 * D_U$ .  $T_{rreq}$  denotes the average time of broadcast packets from sources to destinations and can be written as,  $T_{rreq} = \bar{K} * D_B$ .  $T_{rrep}$  denotes the average time of RREP packets delivered back to sources and can be computed as,  $T_{rrep} = \bar{K} * D_U$ .

## V. DISSECTING MAC PERFORMANCE: EVALUATING MAC PARAMETER TUPLE

The only question left to be answered boils down to characterizing the MAC performance, reflected in the MAC parameter tuple  $\vec{\theta}_m = \{\bar{S}_B, \bar{S}_U, \mathcal{V}_B, \mathcal{V}_U, p_e\}$ , which we do next. Particularly, we consider three representative MAC schemes. One is global time division multiple access (GTDMA [35]), serving as a lower achievable bound. The second one is still a TDMA scheme, but the scheduler is optimally designed (LTDMA [36]). In practice, there is none of such schedulers because it needs instant global topology information and a design of such schedulers is known as NP problem. However, we still consider such schemes, serving the purpose of an upper performance bound for scheduled MAC. Finally, we consider the widely deployed contention-based MAC scheme, 802.11 DCF MAC, targeting at more practical protocol analysis.

### A. Global Time Division Multiple Access

In GTDMA scheme, the channel access of nodes is organized as frames in time and each frame is further organized into  $N$  slots. In every frame, every node in the network is assigned a slot for transmission and the duration of slot should allow nodes to transmit the maximum transmission unit (MTU).

Let  $\Delta_g$  be the duration of a slot and the duration of a framework will be  $\Delta_f = N\Delta_g$ . In such fashion, every node will get one slot to sent out one packet (either broadcast packet or unicast packet) for every  $\Delta_f$  time. During the scheduled access, there will be no collision in packet transmission and thus it is safe to assume that the packet loss probability will be zero, i.e.,  $^2P_e = 0$ . It is also clear that every node enjoys a deterministic service time as of  $\Delta_f$ . For such special case, M/G/1 model is thus reduced to a two-customer M/D/1 model. Correspondingly, one have

$$\begin{aligned} \mathcal{V}_B = \mathcal{V}_U &= 0, \\ \bar{S}_B = \bar{S}_U &= \Delta_f. \end{aligned} \quad (11)$$

### B. Local Geni-TDMA

Contrary to GTDMA, LTDMA is a localized TDMA scheme where the transmission of nodes are scheduled locally. For node  $i$ , if it has  $N_r - 1$  neighbors, the channel access is still grouped as frames but each frame has only  $N_r$  slots for all  $N_r$  nodes, who are within coverage of node  $i$ . However, the design of such a scheduling scheme for all nodes without collisions is sometimes impossible and a NP-hard problem. We assume that there is always one such Geni-scheduler and the obtained results serve as an upper bound on performance.

For such a scheme, the packet loss probability is also zero  $P_e = 0$ . However, it is clear that because of network mobility the number of nodes within a communication circle,  $N_r$ , is a random variable rather than a constant value. By simplifying the analysis in [38] and referring our previous analysis for GTDMA, we represent the service time for LTDMA as a

<sup>2</sup>Please note that we do not consider wireless environmental effects, e.g., fading, conforming to the well-known protocol model [37].

random variable  $S_B = \Delta_g N_r$ , with the average and covariance values as follows

$$\begin{aligned} \mathcal{V}_B = \mathcal{V}_U &= \text{Var}(\Delta_g N_r) = \Delta_g^2 \text{Var}(N_r), \\ \bar{S}_B = \bar{S}_U &= E(\Delta_g N_r) = \Delta_g E(N_r), \end{aligned} \quad (12)$$

where  $\Delta_g$  denotes the time duration of a slot and  $\text{Var}(\cdot)$  is the variance operator of a random variable. If the distribution of nodes is uniform,  $N_r$  will be binomially distributed as

$$\begin{aligned} P(N_r = K) &= C_N^K p^K (1-p)^{N-K}, \\ p &= \pi R^2 / A_n, \end{aligned} \quad (13)$$

where  $p$  is the probability of two nodes being within communication range of each other. Then, one has

$$\begin{aligned} E(N_r) &= N \times p, \\ \text{Var}(N_r) &= N \times p(1-p). \end{aligned} \quad (14)$$

### C. Contention-based MAC

We consider the well-known 802.11 DCF MAC, employing carrier sense multiple access with collision avoidance (CSMA/CA). In such a scheme, broadcast packets and unicast packets are processed differently and will therefore have different service time.

For unicast packets, a rotating back-off mechanism is adopted to resolve contention. For the first trial of transmission of a packet, if the channel is sensed to be idle for an interval greater than Distributed Inter-Frame Space (DIFS), the node initializes a backoff timer. And the value of backoff timer is uniformly selected within the initial contention window (CW)  $CW_{min}$ . The timer decrements when the channel is sensed to be idle, freezes when the channel becomes busy and restarts when the channel becomes idle for a DIFS again. When the timer counts to zero, the packet is transmitted immediately and waits for ACK confirmation. In case that ACK is not received and the last transmission is declared a failure, the value of CW is doubled for retransmission, until it reaches the upper limit of  $CW_{max}$  specified by the protocol.

For broadcast packets, no retransmission is attempted and no ACK is needed. Each broadcast packet is transmitted only once. Therefore, broadcast packets only need to go through the first trial phase of unicast packet transmission, i.e., the phase with the initial contention window of  $CW_{min}$ .

To analyze the MAC performance of a node  $i$ , let's first look at its probability generating function  $C_i(z)$  of channel occupancy observed from node  $i$ . Channel occupancy of node  $i$  is used to characterize the distribution of channel utilizations from its neighboring nodes.  $C_i(z)$  employs a generic representation form as  $C_i(z) = \sum_n P(C_i = n) z^{n+1}$ , where  $C_i$  is expressed in discretized slot duration,  $P(C_i = n)$  denotes the probability of channel being sensed as busy for a continuous period of  $n$  slots and  $z$  is a dummy variable. Such discretized slot representation may introduce some small deviations, however, since the slot duration  $\delta$  is usually a very small value, such discretization effect could be neglected.

Clearly, the identity channel generating function  $C_i(z) = p(C_i = 0)z = z$  would mean that  $n = 0$  always, i.e., the channel is permanently sensed idle by node  $i$ . Since we assume the nominal packet length, which means that all packets sent

to channel should be of the same length  $L$ . Therefore, there are only two kinds of channel states: idle (no packet arrival) and busy (some arrival with packet length  $L$ ). In this case, we can simplify the generating function as  $C_i(z) = (1 - p_a + p_a * z^L) * z$ , where  $p_a$  is the probability of packet arrivals from neighboring nodes at the same time slot. Clearly, it also corresponds to the packet collision probability of node  $i$ , i.e.,  $p_e = p_a$ .

The packets competing with node  $i$  is the summation of traffics from all neighboring nodes. The distribution of such arrival process can be approximated as poisson, deduced from the superposition of random variables. Mathematically, the mean rate  $\lambda_i^c$  of competing traffic can be written as  $\lambda_i^c = E(\sum_{\forall k \in \{\text{neighbors}\}} (\lambda_B^k + \lambda_U^k))$ . Since the expected number of nodes in the communication circle of any node  $i$  (including node  $i$  and all its neighbors) has been derived in Eq. 14 as  $Np$ ,  $\lambda_i^c$  can thus be approximated as  $(Np - 1)(\lambda_B^k + \lambda_U^k)$ . Since a transmission collision occurs when there are competing packets arriving, the packet loss probability, i.e., the probability of collision, could be approximated as the competing traffic rate within the duration of a slot,

$$P_e = \lambda_i^c * \delta \approx (Np - 1)(\lambda_B + \lambda_U) * \delta \quad (15)$$

where  $\delta = 20\mu s$  in 802.11 DCF MAC.

We then look at the service aspect of M/G/1 model under such MAC scheme. Let  $\phi(z, L, \alpha, \gamma)$  be the probability generating function of service delay for each packet, where the collision probability is  $\alpha$  and the back-off window value is  $\gamma$ .  $\phi$  includes channel access time and the time needed to transmit the packet. The back-off counter value  $M$  is uniformly chosen within  $\gamma$  with the probability of  $\frac{1}{\gamma}$ .

Without collision, the total time to access the channel is the time needed for  $M$  decreases, that is,  $M$  times the busy time slot random variable  $C_i$  which can be expressed by generating function  $\sum_{i=1 \dots \gamma} \frac{1}{\gamma} C_i(z)^i$ . Once the channel is accessed, the time needed to transmit the packet is fixed and equal to  $L$ , therefore it can be expressed by generating function  $z^L$ . Hence, the service time when no collision occurs comes from adding the previous two quantities, or equivalently the corresponding generating function is equal to the product of the above generating functions [27], i.e.,

$$\frac{z^L}{\gamma} \sum_{i=1 \dots \gamma} C_i(z)^i = \frac{C_i(z)^{\gamma+1} - C_i(z) z^L}{C_i(z) - 1} \frac{z^L}{\gamma}. \quad (16)$$

Eq.(16) is exactly the probability generating function of service time for broadcast packets, where none of packet collisions is concerned.

In case there is collision, the nodes select a new back-off number in a doubled contention window  $\{1 \dots 2\gamma\}$  and the procedure is repeated which results in an additional service delay term. We obtain the following equation:

$$\begin{aligned} \phi(z, L, \alpha, \gamma) &= \frac{C_i(z)^{\gamma+1} - C_i(z) z^L}{C_i(z) - 1} \frac{z^L}{\gamma} \\ &\times (1 - \alpha + \alpha \phi(z, L, \alpha, 2\gamma)). \end{aligned} \quad (17)$$

Clearly, computing the probability generating function of

service time through Eq.(17) for unicast packets requires a recursive computation until the contention window reaches the maximum value  $CW_{max}$ .

Finally, we can summarize the probability generating function of service time for both broadcast packets  $\phi_B(z)$  and unicast packets  $\phi_U(z)$  as,

$$\begin{aligned} \phi_B(z) &= \frac{C_i(z)^{CW_{min}+1} - C_i(z)}{C_i(z) - 1} \frac{z^L}{CW_{min}}, \\ \phi_U(z) &= \phi(z, L, E(P_e^i), CW_{min}). \end{aligned} \quad (18)$$

The mean service time for broadcast packets and unicast packets can then be computed as,

$$\begin{aligned} \bar{S}_B &= \left( \frac{d}{dz} \phi_B(z) \right) \Big|_{z=1}, \quad \mathcal{V}_B = \left( \frac{d}{dz} \left( z * \frac{d}{dz} \phi_B(z) \right) \right) \Big|_{z=1}, \\ \bar{S}_U &= \left( \frac{d}{dz} \phi_U(z) \right) \Big|_{z=1}, \quad \mathcal{V}_U = \left( \frac{d}{dz} \left( z * \frac{d}{dz} \phi_U(z) \right) \right) \Big|_{z=1}. \end{aligned} \quad (19)$$

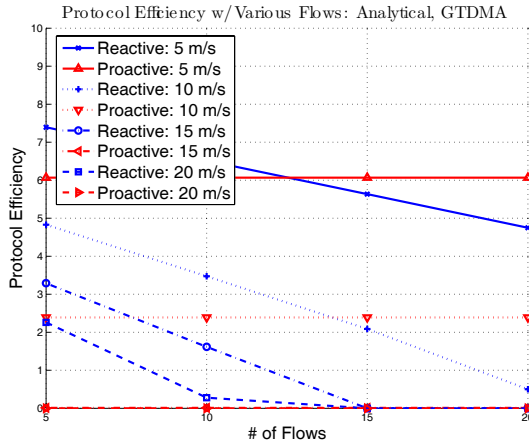
Based on computed values of MAC parameters in tuple  $\vec{\theta}_m = \{\bar{S}_B, \bar{S}_U, \mathcal{V}_B, \mathcal{V}_U, p_e\}$  for specific MAC protocol, we can then calculate performance metrics of routing protocols running on the MAC protocol according to our proposed analytical model, such as protocol efficiency, packet delivery ratio and delay.

## VI. SIMULATIONS

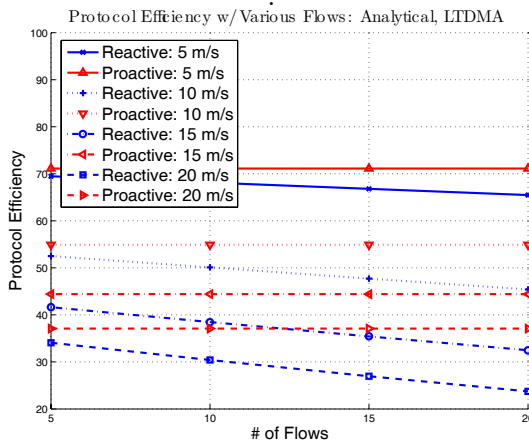
In this section, we aim to validate the effectiveness and correctness of our analytical framework in capturing core behaviors of certain kind of routing protocols, rather than providing precise analysis for specific protocol. We also prove that our analytical model is capable of presenting the effect of various parameters on the performance of routing protocols.

In the simulation, we consider a total of 100 nodes initially randomly distributed over a square network of size  $1000m \times 1000m$ . Every node moves at a speed  $V$  and transmits at uniform power of a coverage of radius  $R$  under certain traffic load. Three different transmission ranges  $R \in \{150, 200, 250\}m$  are covered, all within the coverage of WiFi devices. Four different speeds  $V \in \{5, 10, 15, 20\}m/s$  are simulated, from lower mobility to higher mobility scenarios. Traffic, supplied from a CBR source with fixed packet size of 1000 Bytes, is randomly generated with uniformly distributed sources and destinations. Different number of traffic flows  $F \in \{5, 10, 15, 20\}$  are simulated, covering low and moderate flow configurations. However, for each traffic flow the traffic rate is randomly derived from a generator with exponential distribution and its arrival rate is 0.5. In addition, for each traffic flow the start time is also randomly generated while it is limited in the range of [10% 30%] of the whole simulation time. Once the traffic starts, it will be generated continuously. In addition, simulation results are obtained for both reactive (AODV [32]) protocol and proactive (OLSR [31]) protocol. For the OLSR simulation, we use the default implementation in *Qualnet 3.9.5*; while to match our analytical model for reactive protocols, in AODV simulation we disable intermediate node route reply during route discovery and local repair for route maintenance. The MAC layer is chosen as the default implementation of 802.11 MAC in *Qualnet*. Overall, a total of 120 different {radius, mobility, flow, protocol} configurations





(a) Analytical, GTDMA



(b) Analytical, LTDMA

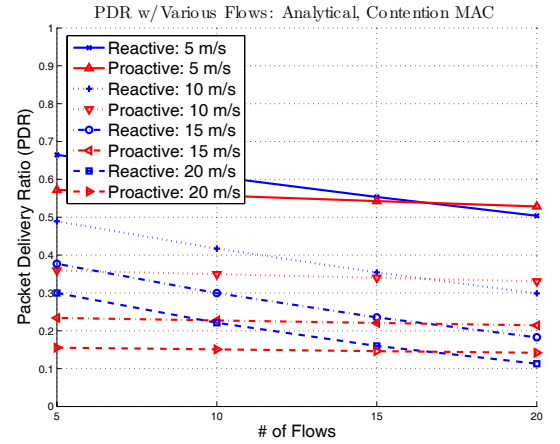
Fig. 1. Protocol efficiency, various flows.

are simulated. For each configuration, the simulation result is obtained from 10 random runs. Each simulation run is conducted with a randomly generated seed with a duration of 30 minutes.

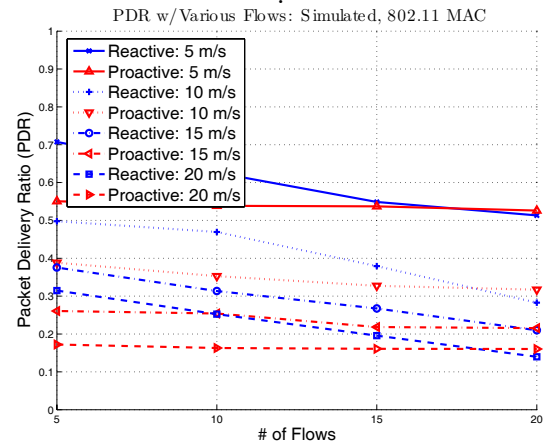
Since our proposed analytical model includes both MAC and network layer parameters, we can comply two steps to evaluate certain kind of routing protocol under specific network configurations.

- First, check which kind of MAC protocol the system employs and derive corresponding MAC parameter values, such as service time and packet loss probability.
- Second, check which kind of routing protocol it is (proactive or reactive), and then use previously derived MAC parameters and corresponding equations constructed in our analytical model to derive various evaluation metrics, such as protocol efficiency, delivery ratio, delay and so on.

We first demonstrate the effectiveness of our parametric framework in exploring the compounding and interacting effect of network parameters on the performance of routing protocols. We derive the protocol efficiency of routing protocols running on two different MAC protocols shown in Fig. 1 (a) and (b). From them, we can see that GTDMA provides very low throughput (measured by protocol efficiency) and



(a) Analytical, Contention-based MAC



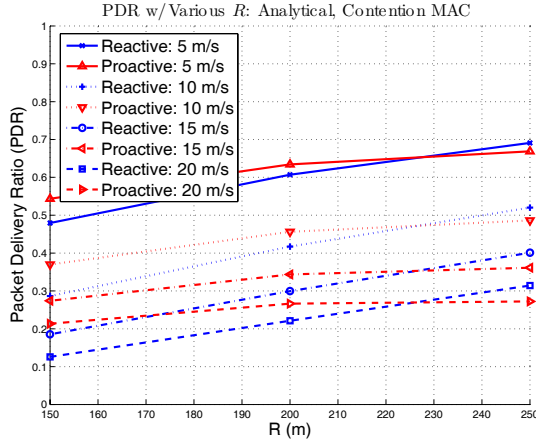
(b) Simulated, 802.11 MAC

Fig. 2. Packet delivery ratio (PDR), various flows.

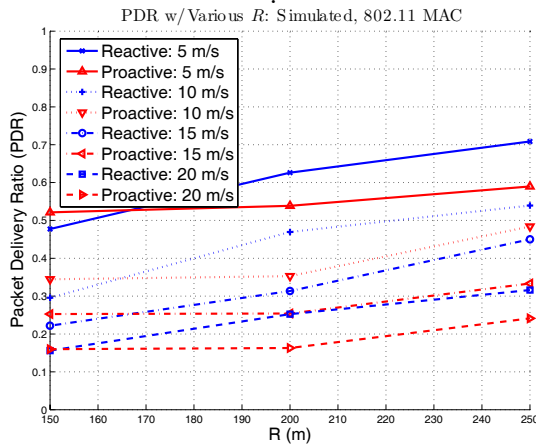
hit the bound of network scalability, while LTDMA scheme still enjoys good performance which illustrates that the design of MAC layer significantly affects protocol performance and network scalability.

We secondly present the effectiveness of our model in providing the deeper understanding on essential protocol behaviors. Fig. 2 shows packet delivery ratio (PDR) for both proactive and reactive protocols under various {mobility, traffic flow} configurations. Fig. 2 (a) shows results derived from our analytical model, while Fig. 2 (b) shows results derived from simulation.

- Although differences exist between analytical and simulation results for both reactive and proactive protocols, our analytical results provide a satisfactory approximation to the simulated performance. Our model succeeds in capturing the core behavior of routing protocols, which is the main goal of our work.
- Fig. 2 also demonstrates that our model could be used for performance analysis. For example, from Fig. 2(a) our analytical results reveal that reactive protocols are more susceptible to traffic increase, i.e., they represent an obvious PDR decreasing trend as the number of traffic flows increases, while proactive protocols are robust to change in traffic. In general, as traffic increases, a cross-



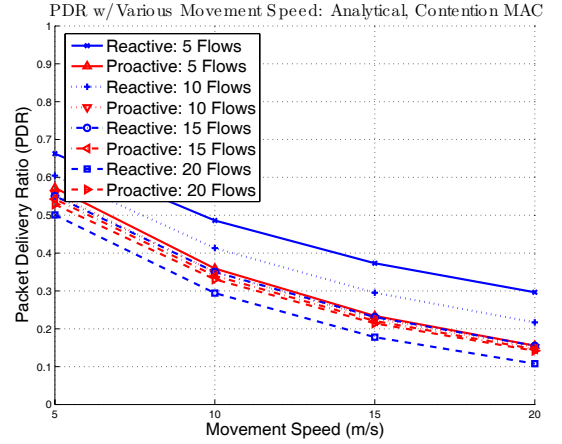
(a) Analytical, Contention-based MAC



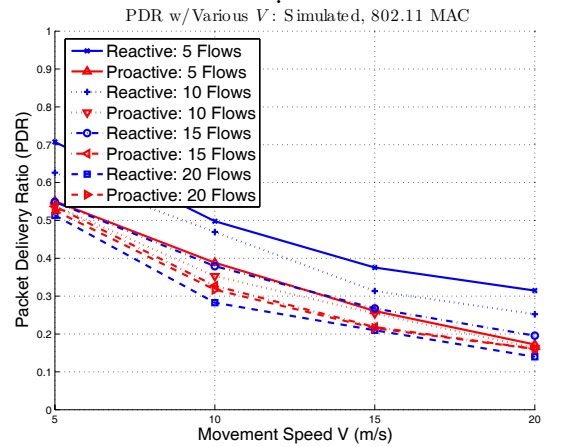
(b) Simulated, 802.11 MAC

Fig. 3. Packet delivery ratio (PDR), various  $R$ .

- point should be expected to signal the transition of preference to proactive protocols. The analytical findings corroborates similar simulation findings in Fig. 2(b) and literatures [14], [15].
- Since our analytical model focuses on core behaviors of proactive and reactive protocols while in simulation tool protocols are fully implemented, the difference between analytical and simulation results could be expected and reasonable. Note that when evaluating reactive protocols, since there is no specific analysis for AODV protocol implemented in Qualnet and our analytical model aims to provide analysis for core behaviors of reactive protocols, the general reactive protocol described in Section III-D2 is used. That is, as we stated previously, during our simulation we employ junior AODV without intermediate node route reply and local repair. However, when evaluating proactive protocols, the proposed model has been adapted by adjusting the value of that constant parameter  $c_1$  in the mean link lifetime of  $T_L$  to incorporate Multipoint Relays (MPR) technique studied in the specific analysis for OLSR protocol in [29]. This demonstrates the capability of our model approximating practical performance with protocol specific technique incorporation.
  - We admit that our analytical model may not provide



(a) Analytical, Contention-based MAC



(b) Simulated, 802.11 MAC

Fig. 4. Packet delivery ratio (PDR), various  $V$ .

an exact analysis for a specific routing protocol, which may be caused by many reasons: our model is based on core routing behaviors and makes some assumptions which may not be held in simulation; the incorporation is partial and the adapted model is still not a comprehensive analysis for the specific protocol; the analytical model is constructed on statistical processes and could not capture all practical and dynamic factors.

It should be noted that in the above figures we only present the relationship between PDR and various number of flows. Therefore, now we look at one theoretical aspect of the model and are interested to know how the increment in transmission radius  $R$  affects protocol performance under various {mobility, transmission radius} configurations. Fig. 3 (a) from the model immediately brings out the answer. The increase in  $R$  results in two conflicting effects: improvements in *logic efficiency*, resulting from the shorter source-destination distance; deterioration in *operation efficiency* with more competing neighbor nodes. The analytical explanations well agree with our intuition which is validated by simulation in Fig. 3 (b). Clearly, our analytical model is essential not only to confirm and complement the simulations, but also to supply inherent clues to how changes in network parameters translate into performance variations.

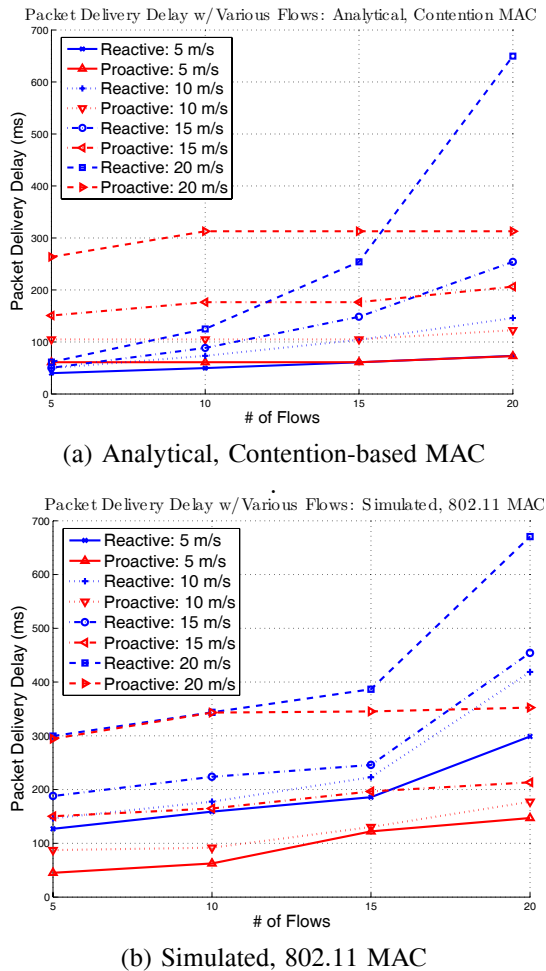


Fig. 5. Packet delivery delay, various flows.

We also demonstrate how well our analytical model does in capturing the nodes mobility effect on the packet delivery ratio of both proactive and reactive routing protocols in Fig. 4 (a) and (b). The larger the nodes movement speed is, the larger the probability of nodes moving out of transmission range is. Then the relay failure probability increases which causes the PDR decrease. Both analytical and simulation results agree with this intuition, i.e., our model provides excellent match to simulated performance for both reactive and proactive routing protocols.

Similarly, our parametric analytical framework could also capture the essential insights and behaviors of routing protocols in terms of packet delivery delay under various network scenarios. We hereby demonstrate that by observing the packet delivery delay with various traffic flow  $F$  in Fig. 5. Theoretically (shown in Fig. 5 (a)), proactive routing protocols periodically update routing path information to guarantee packets being sent out immediately, therefore even arrival packet number increases as traffic flow increases, they still can be sent out in time which causes the stability of packet delivery delay; however, for reactive routing protocols heavy traffic constraints the routing request process which increases the packet delivery delay. Simulation results in Fig. 5 (b) for both proactive and reactive routing protocols validate our theoretical model. Note that we achieve good match

between analytical and simulation results for proactive routing protocols. However, for reactive routing protocols obvious difference between them for light traffic exists which is expected and reasonable, since AODV implemented in Qualnet includes periodical Hello message scheme to detect link failure which causes the waiting time of routing packets increase for being sent out and in turn causes packet delivery delay larger than that derived from our analytical model which aims to present essential behaviors and does not include Hello message scheme for reactive routing protocols. Especially, when the number of traffic flows is small, packet delivery delay without Hello messages is small and the effect of nodes' movement is not obvious which is shown in our analytical result in Fig. 5 (a).

## VII. CONCLUSIONS

We presented an analytical framework to evaluate the behavior of generic reactive and proactive protocols. In the model, the operation of the routing protocol is synthesized with the analysis of the MAC protocol to produce a parametric characterization of protocol performance. The effectiveness and correctness of the model are corroborated with extensive simulations. The model enables in-depth understanding of routing protocol performance, and points out the need to design routing protocols that are capable of confining signaling overhead to those portions of the network where the routing information is needed, in order to operate efficiently under different types of mobility and traffic patterns. A similar conclusion can be derived by looking at the capacity of ad hoc networks under different types of information dissemination [39]. In our future work, we plan to incorporate realistic physical layer effect into our modeling framework to make it more practical and comprehensive.

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## REFERENCES

- [1] S.-Y. Ni, Y.-C. Tseng, Y.-S. Chen, and J.-P. Sheu, "The broadcast storm problem in a mobile ad hoc network," in *Proc. ACM Mobicom 1999*, New York, pp. 151-162.
- [2] S. Das, R. Castaneda, J. Yan, and R. Sengupta, "Comparative performance evaluation of routing protocols for mobile ad hoc networks," in *Proc. 7th International Conf. Computer Commun. Netw. (IC3N)*, Lafayette, LA, USA, Oct. 1998, pp. 153-161.
- [3] F. Bertocchi, P. Bergamo, G. Mazzini, and M. Zorzi, "Performance comparison of routing protocols for ad hoc networks," in *Proc. IEEE GLOBECOM*, vol. 2, San Francisco, CA, USA, Dec. 2003, pp. 1033-1037.
- [4] 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," *IEEE Personal Commun. Mag.*, vol. 8, no. 1, pp. 16-28, Feb. 2001.
- [5] J. Broch, D. A. Maltz, D. B. Johnson, Y. C. Hu, and J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols," in *Proc. 4th Annual ACM/IEEE International Conf. Mobile Comput. Netw.*, New York, Oct. 1998, pp. 85-97.
- [6] L. Viennot, P. Jacquet, and T. H. Clausen, "Analyzing control traffic overhead versus mobility and data traffic activity in mobile ad-hoc network protocols," *ACM/Springer Wireless Netw.*, vol. 4, no. 10, pp. 447-455, July 2004.
- [7] N. Zhou, H. Wu, and A. A. Abouzeid, "Reactive routing overhead in networks with unreliable nodes," in *Mobicom'03*, San Diego, Sept. 2003.

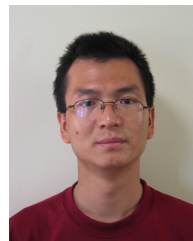
- [8] N. Zhou, H. Wu, and A. Abouzeid, "The impact of traffic patterns on the overhead of reactive routing protocols," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 3, pp. 547-560, Mar. 2005.
- [9] N. Zhou and A. Abouzeid, "Routing in ad hoc networks: a theoretical framework with practical implications," in *Proc. 24th Annual Joint Conf. IEEE Computer Commun. Societies (INFOCOM)*, vol. 2, Miami, FL, USA, Mar. 2005, pp. 1240-1251.
- [10] —, "Information-theoretic lower bounds on the routing overhead in mobile ad-hoc networks," in *Proc. IEEE International Symp. Inf. Theory (ISIT)*, vol. 2, Yokohama, Japan, June 2003.
- [11] A. Tsirigos and Z. J. Haas, "Analysis of multipath routing—part 1: the effect on the packet delivery ratio," *IEEE Trans. Wireless Commun.*, vol. 3, no. 2, pp. 500-511, Mar. 2004.
- [12] —, "Analysis of multipath routing—part 2: mitigation of the effects of frequently changing network topologies," *IEEE Trans. Wireless Commun.*, vol. 3, no. 1, pp. 138-146, Jan. 2004.
- [13] P. Johansson, T. Larsson, N. Hedman, and B. Mielczarek, "Scenario-based performance analysis of routing protocols for mobile ad-hoc networks," in *Proc. 5th ACM/IEEE MOBICOM*, Seattle, WA, USA, 1999, pp. 195-206.
- [14] S. J. Lee, M. Gerla, and C. K. Toh, "A simulation study of table-driven and on-demand routing protocols for mobile ad hoc networks," *IEEE Network*, vol. 13, no. 4, pp. 48-54, 1999.
- [15] J.-W. Chen, Y.-Z. Lee, D. Maniezzo, and M. Gerla, "Performance comparison of AODV and OLSR in wireless mesh networks," in *IFIP MEDHOCNET*, Lipari, Italy, June 2006.
- [16] A. Al-Maashri and M. Ould-Khaoua, "Performance analysis of MANET routing protocols in the presence of self-similar traffic," in *Proc. 31st IEEE Conf. Local Computer Netw.*, pp. 801-807, Jan. 2006.
- [17] P. long Yang, C. Tian, and Y. Yu, "Analysis on optimizing model for proactive ad hoc routing protocol," in *Proc. Military Commun. Conf. (MILCOM)*, vol. 5, Atlantic City, NJ, USA, Oct. 2005, pp. 2960-2966.
- [18] D. Lebedev, "A framework for the comparison of AODV and OLSR protocols," *Technol. Advanced Heterogeneous Netw.*, pp. 98-111, 2005.
- [19] I. Bacarrea Nogaes, "Model and performance analysis of mobile ad-hoc wireless networks," in *Proc. 17th International Conf. Radioelektronika*, Prague, Czech Republic, Apr. 2007, pp. 1-6.
- [20] P. Jacquet and A. Laouiti, "Analysis of mobile ad-hoc network routing protocols in random graph models," 2000. [Online]. Available: [citeseer.ist.psu.edu/jacquet99analysis.html](http://citeseer.ist.psu.edu/jacquet99analysis.html)
- [21] C. Perkins and E. Royer, "Ad-hoc on-demand distance vector routing," in *Proc. 2nd IEEE Workshop Mobile Computing Syst. Appl.*, vol. 2, pp. 90-100, 1999.
- [22] P. Jacquet, P. Muhlethaler, T. Clausen, A. Laouiti, A. Qayyum, and L. Viennot, "Optimized link state routing protocol for ad hoc networks," in *Proc. IEEE INMIC*, pp. 62-68, 2001.
- [23] C. Bettstetter, "Mobility modeling in wireless network: categorization, smooth movement and border effects," *ACM Mobile Computing Commun. Review*, vol. 5, pp. 55-67, Jan. 2001.
- [24] W. Navid and T. Camp, "Stationary distributions for the random waypoint model," *IEEE Trans. Mobile Computing*, vol. 3, no. 1, pp. 99-108, 2004.
- [25] J. Yoon, M. Liu, and B. Noble, "Sound mobility models," in *ACM Mobicom 2003*, San Diego, CA.
- [26] J.-Y. L. Boudec and M. Vojnovic, "Perfect simulation and stationarity of a class of mobility models," in *INFOCOM 2005*, Miami, FL.
- [27] G. Rodolakis, "Analytical models and performance evaluation in massive mobile ad hoc networks—chapter 2.2," Ph.D. dissertation, Ecole Polytechnique, 2006.
- [28] L. Kleinrock, *Queueing Systems, Volume 1: Theory*. John Wiley & Sons, Inc., 1975.
- [29] X. Wu, H. R. Sadjadpour, and J. J. Garcia-Luna-Aceves, "Modeling of topology evolutions and implication on proactive routing overhead in MANETs," *Elsevier Computer Commun. J.*, special issue on algorithmic theoretical aspects of wireless ad hoc sensor networks, 2007.
- [30] D. P. Heyman and M. J. Sobel, *Stochastic Models in Operations Research*. New York: McGraw-Hill, 1982, vol. I.
- [31] T. Clausen and P. Jacquet, *Optimized Link State Routing Protocol (OLSR)*. IETF RFC 3626, 2003.
- [32] C. E. Perkins and E. M. Royer, "Ad hoc on-demand distance vector routing," in *Proc. 2nd IEEE Workshop Mobile Computing Syst. Appl.*, New Orleans, Feb. 1999, pp. 90-100.
- [33] X. Wu, H. R. Sadjadpour, J. J. Garcia-Luna-Aceves, and H. Xu, "A hybrid view of mobility in MANETs: analytical models and simulation study," *Elsevier Computer Commun. J.*, vol. 31, pp. 3810-3821, 2008.
- [34] X. Wu, H. R. Sadjadpour, and J. J. Garcia-Luna-Aceves, "Link lifetime as a function of node mobility in manets with restricted mobility: modeling and applications," in *WiOpt 2007*, Apr. 2007.

- [35] I. Rubin, "Access-control disciplines for multi-access communication channels: reservation and TDMA schemes," *IEEE Trans. Inf. Theory*, vol. 25, no. 5, pp. 516-536, 1979.
- [36] R. Nelson and L. Kleinrock, "Spatial TDMA: a collision-free multihop channel access protocol," *IEEE Trans. Commun. [legacy, pre-1988]*, vol. 33, no. 9, pp. 934-944, 1985.
- [37] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 388-404, Mar. 2000.
- [38] T. A. F. Kostas, A. H. Haddad, and C. C. Lee, "Performance analysis of a dynamic bandwidth allocation algorithm for a mixed traffic TDMA network," *IEEE Trans. Veh. Technol.*, vol. 56, no. 4, pp. 2306-2320, 2007.
- [39] Z. Wang, H. R. Sadjadpour, and J. J. Garcia-Luna-Aceves, "A unifying perspective on the capacity of wireless ad hoc networks," in *IEEE Infocom 2008*, Apr. 2008.



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