Queueing Models for the Performance of Multihop Routing in a Intermittently-Connected Mobile Network

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***Abstract*—Consider an intermittently-connected mobile ad-hoc network with a single source/destination aided by n mobile relay nodes each of which has a finite storage buffer. In this paper we develop, for the first time, an analysis of the steady-state performance of multihop routing in such a network with a general mobility model and characterize it in terms of throughput and transmission-cost overhead. We investigate whether multihop routing has any potential for improvement over two hop routing. We show that analytical models for performance under multihop can be obtained by employing queuing-theoretic techniques and embedded-Markov-chain identification. The solution offered is in the form of non-linear steady-state equations which can be efficiently solved iteratively. The key outcome of this work is that multihop can indeed improve upon two-hop routing in the finite-buffer regime, by means of mitigating the reduction in throughput caused by limited storage (leading to blocking/saturation of buffers). However, the improvement in throughput diminishes as the buffer size grows, and comes at the cost of additional relay-to-relay transmissions.**

I. Introduction

Intermittently-Connected Mobile Ad-Hoc Networking (ICMANET) involves scenarios wherein end-to-end connectivity resulting from a multihop path from the source to the destination node almost never occurs. Hence, the only viable option in such a network is to employ one of several routing protocols based on the *store, carry, and forward* paradigm (also known as *mobility-assisted routing*) of communication [1], [2]. Under this paradigm, the source node opportunistically transmits packets (intended for a specific destination) to any other node that it comes in contact with, and relies on the mobility of these "relay" nodes to convey them to the intended destination eventually. In this paper, we develop analytical models to characterize the performance of multihop routing for unicast communication in such networks, in terms of the achievable throughput and the transmission cost. We also show that the proposed framework is applicable to any mobility model that exhibits *statistical time stationarity*.

In recent literature [3], [4], performance analysis of ICMANETs (also known as Delay/Disruption-Tolerant Networking or DTNs in certain contexts) has taken the approach of modeling contacts using the Poisson process. In contrast, our framework seeks to obtain a more generalized analytical framework that does not depend heavily on very specific assumptions about the mobility model. In other works such as [5], real-world-like physical model is assumed, but the node memory is assumed to be unlimited. Moreover, the analysis in [5] applies to the case where traffic is bursty and sparse. In our past work on two-hop routing [6]–[8], we developed an analytical framework and showed that it works in two-hop scenarios. In this paper, we extend our two-fold approach developed in [6], [7] that combines 1) Embedded Markov-Chain identification, and 2) Chain reduction by state-collapsing, for the case of multi-hop routing. This leads to a set of non-linear steady-state equations, for which we develop an efficient low-complexity iterative method for the steady-state performance of such a system, based on queuing-theoretic analysis. Our approach yields accurate results while incorporating practical considerations such as finite node buffers, random contention, finite communication range, and random mobility. Steady-state analysis is taken up since it offers a suitable definition for throughput under packet-based routing protocols developed for DTNs, such as [9], [10]. Finally, we validate the analysis using simulations for two different mobility models: the random-walk-on-grid and the restricted-random-waypoint models.

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II. Network Model

Since the analysis presented in our previous work [6], [7] is extended here for multihop routing, we use more or less the same network model. Key aspects of the model and the important modifications for multihop routing alone are described here. Further details on the model can be found in [6], [7].

In a given ICMANET, whenever two nodes (devices) are within communication range of each other, we say that a "contact" has occurred between them. However, they may only communicate when a "link" exists between them. A "block" of packets, say q in number, can be transmitted through any link in one epoch. Hence q is related to the transmission bandwidth in the network.

The network consists of a single source-destination pair and n relay nodes with a buffer space of B blocks each. Nodes are characterized by a certain finite communication range, K within which they are able to send or receive packets from another node. The source, destination, and relay nodes are characterized by the identical (but independent) mobility processes. We consider our network to be operating in discrete time, where time is sliced up into several epochs. At every epoch, a single block may be transmitted/received across a link. Since we are not interested in characterizing the effect of channel loss on throughput, but on higher-layer effects, we assume loss-free transmissions though the framework can be extended to the lossy case.

A. Mobility Model

The underlying mobility model is assumed to exhibit wide-sense statistical stationarity. The mobility of any node v is denoted by a random process $\chi_v(t)$, which at each instant t is a probability distribution on a discrete state-space $\mathcal{S}_{mob}$ of the given mobility model. The state transition function $\boldsymbol{\Psi_{mob}}(\cdot)$ is now described. Let $\mathbf{p}(t)$ be the probability distribution of the node's mobility state at time t. Also, let the mobility model have a memory of

m' time-steps, where m' is a positive integer. Then, we have:

$$\mathbf{p}(t+1) = \mathbf{\Psi_{mob}}\left[\mathbf{p}(t), \mathbf{p}(t-1), \cdots, \mathbf{p}(t-m')\right] \text{ for } t > m'.$$

Since the mobility model is assumed to be wide-sense stationary, it has a unique steady-state distribution $\boldsymbol{\pi}_{mob}$ that satisfies

$$\boldsymbol{\pi}_{mob} = \mathbf{\Psi_{mob}}\left[\boldsymbol{\pi}_{mob}, \cdots, \boldsymbol{\pi}_{mob}\right].$$

B. Multihop Single-Copy Routing

As in [6], [7] we employ single-copy routing, which is justifiable for packetized routing schemes such as [9], [10] where replicating packets is not beneficial. A mobile (relay) node accepts packets from the source node whenever a link is established with the same, retains each packet until a link with the particular destination or with a suitable relay node occurs. Direct source-destination links, whenever they occur, are also exploited. Unlike two-hop routing [6], [7], relay-to-relay communication is also exploited in addition to the direct source-to-relay and relay-to-destination cases. Two relay-nodes while establishing contact exchange their buffer-occupancy states (number of blocks held by the buffer). If the difference in the buffer occupancies is more than or equal to 2 blocks, the relay with the higher occupancy transmits one block of packets to the relay with the lower occupancy, thereby increasing the occupancy of the latter by one block and decreasing that of itself by one block.

C. Contention Resolution and Link Establishment

If the source node and destination node are in direct contact, a link is always established irrespective of the presence of other relay nodes. Otherwise, if several relay nodes and a source/destination node are in contact, any relay node is equally likely to establish a link with the source/destination node. Finally, if several relay nodes are in contact and the source/destination nodes are not reachable from any of the relays, any pair of relay nodes is equally likely to establish a link. Any node other than the intended transmitter within the communication range of a receiving node is not allowed to transmit.

III. Details of the Analysis

A. Notations

Relay nodes in the network is identified by a unique integer, $v \in \{1, 2, \cdots, n\}$. For a Markov Chain $X(t)$ with state-space Ω, the steady-state probability of any state $x \in \Omega$ is denoted by $\pi(x)$. The vector $\boldsymbol{\pi}$ denotes the steady-state distribution for the entire state-space $\mathcal{S}_{mob}$.

B. Overview of the Concept

Our approach for performance analysis is as follows: We first identify an embedded Markov chain that describes the exact dynamics of communication, and show that by identifying certain "desirable" states of the network and analyzing their steady-state probability distributions, one can compute the throughput. This is further facilitated by the "chain collapsing" tool which drastically reduces the complexity of the underlying chain. We devote the rest of the discussion to developing the above steps for multihop routing to obtain an analytical framework that can be solved iteratively.

C. State-space Description and Throughput

The state of any node v at time t in the network is designated by an ordered pair consisting of mobility-state and its buffer-occupancy, as $(\chi_v(t), b_v(t))$. In other words, at any epoch t, $\chi_v(t) \in \mathcal{S}_{mob}$, $0 \leq b_v(t) \leq B$ at any time t for any node v. Next, we define the state of the entire network as the $2(n+1)$-tuple $\mathcal{Y}(t) \triangleq (\chi_1(t), \cdots, \chi_n(t), b_1(t), \cdots, b_n(t), \chi_s(t), \chi_d(t))$. Here, χ_s and χ_d are the mobility states of the source and the destination. The transitions of the process $\mathcal{Y}(t)$ within its state-space can be determined from the mobility model and the underlying communication protocols. With the above state-space description of the network, we define the achievable throughput as the *expected rate at which packets are transferred from s to d when the network is in steady-state*. In essence, we have to analyze the complex multi-dimensional random process $\mathcal{Y}(t)$ in order to derive the throughput for the ICMANET network model. Clearly, the full state-space description of the network, consisting of $\Theta\left(B^n|\mathcal{S}_{mob}|^{n+2}\right)$ states, is prohibitively large to work with. In order to reduce the size of the state space, we use the three-step procedure developed in [7] to obtain a Markov chain of smaller size which is easier to analyze.

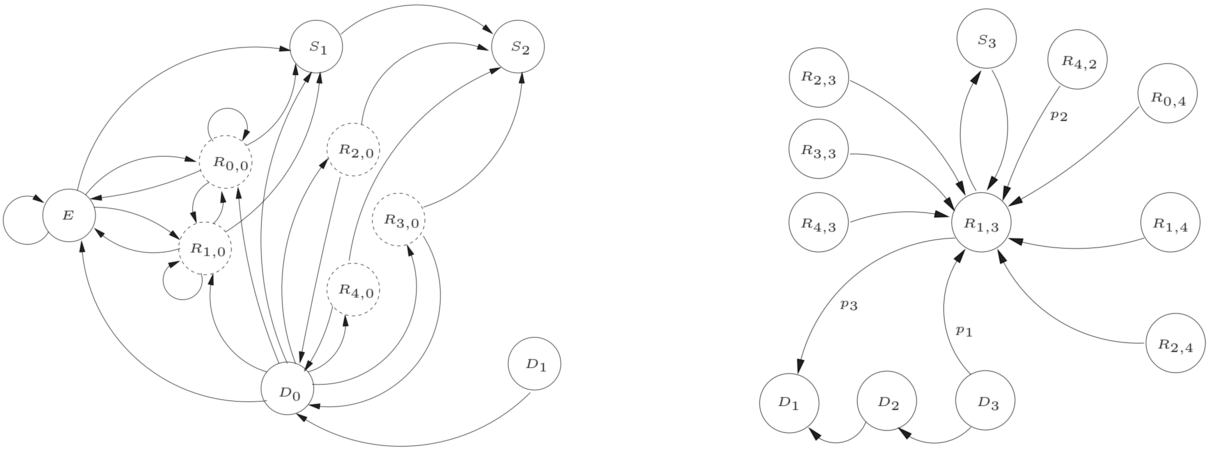
D. Embedded Markov Chain and Chain Collapsing

We now extend the detailed procedure devised in [7] for multihop routing. As before, we can view the state of the network from a single relay-node's perspective, compute the throughput due to that node, and scale it up by n. However, this would still leave us with $\Theta\left(B|\mathcal{S}_{mob}|^{n+2}\right)$ states, since the contention effects due to the other nodes' mobility have to be fully accounted for. We can then (1) Derive a Markov Chain from $\mathcal{Y}(t)$ such that the steady-state probability distribution and the transition probabilities of $\mathcal{Y}(t)$ at steady-state are preserved. (2) For a particular relay node v, identify all the "desirable" states in which packets are sent to the destination by v, and certain additional "auxiliary", such that one can construct an "embedded" Markov chain with the combined set. Subsets of desirable and auxiliary states are then grouped together suitably. We then apply "Chain collapsing" (see Theorem 2 in [7]) over this partitioning of the state-space in order to obtain a fresh "collapsed embedded" Markov chain in which states correspond to subsets of states in the original embedded chain. These steps are detailed below.

E. Construction of the Collapsed Embedded Chain

Let v be a particular relay node in the network. We consider the following groups of states from the full-state Markov-chain description of the network $\mathcal{Y}(t)$:

- *S-group and D-group subsets:* S_l, with $1 \leq l \leq B$ is the set of possible network states wherein the *most recent* link that node v was involved in was with the source, resulting in l blocks of q packets in the buffer after communicating with the latter. Similarly, define $D_{l'}$, for all $B-1 \geq l' \geq 0$ to account for communication with the destination.
- *E-group and F-group states:* F is the set of possible network states wherein the most recent link that node v was involved in was with the source, but v was unable to communicate with the latter due to lack of enough buffer space (i.e., Full/saturated buffer condition). Similarly, define E to account for the case when a link is established with the destination when the buffer-occupancy of v is zero.



(a) Inclusion of R-states into the collapsed chain

(b) Transitions into R-states illustrated

Fig. 1: Composition of the Γ_v-chain illustrated for $B = 4$.

- *R-group states:* R_{l_1,l_2} is the set of states such that the last contact that node v had was with a relay node v'. Moreover, v' and v had l_1 and l_2 blocks respectively in their buffers before they exchanged any packets.

Using the above subset partitioning, we then obtain an embedded Markov chain by "chain collapsing" (See [7]), resulting in only $(B+1)^2 + 2(B+1)$ states. Let us call this the Γ_v-chain for the network. Our aim is to find an efficient way to compute the steady-state probability distribution of the states in Γ_v (which we denote by the vector $\boldsymbol{\pi}$) so that one can avoid the cumbersome simulations involving several nodes.

The structure of Γ_v, shown in Fig. 1(a), consists of an additional $(B+1)^2$ states corresponding to relay-to-relay packet exchanges, in addition to the states in the embedded chain corresponding to the two-hop case [7]. Figure 1(b) illustrates the possible states from which node v possessing 3 block can come into contact with another relay possessing 1 block (before receiving packets from v) for the case when $B = 4$. The entire chain needs to be constructed thus for any given B. The task that remains to be done is the computation of the transition probabilities, in terms of the networking and mobility parameters, between various states (i.e., p_1, p_2, p_3 etc. in Fig. 1(b)), which we discuss in the following subsection.

F. Computation of Transition Probabilities and Steady-State Distributions for the Γ_v-Chain

We define the quantity $\alpha(n)$ (to be determined later explicitly in terms of known network parameters) in the following manner: given that a particular relay node u that currently has a link with a source/destination/relay-node u', $1-\alpha(n)$ is the probability that u will establish a link with u' again before establishing one with any other node in the network. Next we note that since the node mobilities are not correlated, the probability that the node u will link again with some other node v' different from u' is exactly given by $\frac{\alpha(n)}{n}$ for each v'. We will later proceed to express $\alpha(n)$ as a function of (i) Mobility parameters, (ii) Networking parameters, and (iii) Contention protocol. Next, we define the following probabilities for the Γ_v-chain:

- Given that v currently has a link with the source, the probability that its next link will be with the source again is given by p_{ss}, and the probability that its next link will be with the destination node is given by p_{sd}. Similarly, one can define p_{dd} and p_{ds} in the same manner.
- Given that v currently has a link with some relay node, the probability that the next link will be with the same/another relay node is given by p_{rr}. Similarly, we can define p_{sr}, p_{dr}, p_{rs}, and p_{rd}.

Due to the symmetry of our network model and due to independent mobility, one can easily verify that these probabilities are given in terms of $\alpha(n)$ by the following equations:

$$\begin{aligned}
p_{ss} &= p_{dd} = 1-\alpha(n) \\
p_{rr} &= p_{ss} + \frac{n-2}{n}(1-p_{ss}) \\
p_{sd} &= p_{ds} = p_{rd} = p_{rs} = \frac{\alpha(n)}{n} \\
p_{sr} &= p_{dr} = \frac{n-1}{n}(1-p_{ss}).
\end{aligned}$$

The transitions into the R-states are slightly more complicated. We discuss these transitions in the proof of the following theorem, summarizing the construction of the entire embedded Markov Chain:

Theorem 1: Let $\varphi_{l_1,l_2} \triangleq \frac{\pi\left(R_{l_2,l_1}\right)}{\sum_{j=0}^{B}\pi\left(R_{j,l_1}\right)}$ for any $0 \le l_1, l_2 \le B$. Then, the steady-state distribution for Γ_v is given by the following system of equations:

$$\begin{aligned}
\pi(E) &= p_{dd}\{\pi(E)+\pi(D_0)\} \\
&\quad + p_{rd}\{\pi(R_{0,0})+\pi(R_{1,0})\} \qquad (1) \\
\pi(F) &= p_{ss}\{\pi(F)+\pi(S_B)\} \\
&\quad + p_{rs}\{\pi(R_{B,B})+\pi(R_{B-1,B})\} \qquad (2)
\end{aligned}$$

$$\pi(D_k) = \begin{cases} p_{dd}\pi(D_{k+1}) + p_{sd}\pi(S_{k+1}) \\ \quad + p_{rd}\left\{\sum_{j=0}^{k}\pi(R_{j,k+2}) + \sum_{j'=k}^{k+2}\pi(R_{j',k+1}) \right. \\ \quad \left. + \sum_{j''=k+2}^{B}\pi(R_{j'',k})\right\}, & 0 \le k \le B-2 \\ p_{sd}\{\pi(F)+\pi(S_B)\} + p_{rd}\{\pi(R_{B-1,B}) \\ \quad + \pi(R_{B,B})\}, & k = B-1 \end{cases} \qquad (3)$$

$$\pi(S_k) = \begin{cases} p_{ds}\{\pi(E)+\pi(D_0)\} + p_{rs}\{\pi(R_{1,0}) + \pi(R_{0,0})\}, \quad k=1 \\ p_{rs}\left\{\sum_{j=0}^{k-2}\pi(R_{j,k}) + \sum_{j'=k-2}^{k}\pi(R_{j',k-1}) + \sum_{j''=k}^{B}\pi(R_{j'',k-2})\right\} \\ +p_{ss}\pi(S_{k-1}) + p_{ds}\pi(D_{k-1}), \quad 1<k\le B \end{cases} \tag{4}$$

For any $0 \le l_1 \le B, \varphi_{l_1,l_2}^{-1}\pi(R_{l_1,l_2})$

$$= \begin{cases} p_{dr}\{\pi(E)+\pi(D_0)\} \\ +p_{rr}\{\pi(R_{0,0})+\pi(R_{1,0})\}, \text{ where } l_2=0 \\ p_{sr}\{\pi(F)+\pi(S_B)\} + p_{rr}\{\pi(R_{B,B}) \\ +\pi(R_{B-1,B})\}, \text{ where } l_2=B \\ p_{sr}\pi(S_{l_2}) + p_{dr}\pi(D_{l_2}) \\ +p_{rr}\left\{\sum_{j=0}^{l_2-1}\pi(R_{j,l_2+1}) + \sum_{j'=l_2-1}^{l_2+1}\pi(R_{j',l_2}) + \sum_{j''=l_2+1}^{B}\pi(R_{j'',l_2-1})\right\}, 0<l_2<B \end{cases} \tag{5}$$

Proof: The proof for the steady state equations (1)-(4) follow from the previous discussion in this section. We only need to analyze the transitions into the R-states. Given that the current link for node v is with a source, destination, or some relay, the probability that the next link is with any of the $n-1$ other relays is given exactly by the quantity p_{rr}. Now in order to determine the probability that the relay node corresponding to the new link has exactly l_1 blocks of q packets in its buffer, we can use the chain collapsing principle. Equivalently, we only need to determine the "subset-averaged" probability distribution of the buffer occupancy of the any relay node every time v comes into contact with the same. By symmetry, we can say that this distribution, denoted as φ above is exactly the same as the distribution of node v every time it comes into contact with a relay node that has occupancy l_1. We call φ as the "joint buffer-occupancy" distributions for the chain Γ_v. Hence, the expression for φ is exactly as given in (5). Knowing this, we can then compute the steady-state probability of each R-state by carefully examining the possible previous states for v in Γ_v. ■

The analysis of steady-state for the Γ_v chain would be complete once we determine the unknown parameter $\alpha(n)$ in terms of networking and mobility parameters. Note that this expression holds for any mobility model that has a unique steady-state probability distribution on its state space. The solution is given by the following theorem:

Theorem 2: Let T_0 denote the random inter-contact time dictated by the mobility process and the link model. Let $T_{\infty,n} \ge 0$ be the random time to wait until contact with one of n other nodes occur, given that at $t=0$ the nodes in question are distributed randomly in the deployment region according to the steady-state distribution of the mobility model. Let EGF_{T_0} be the *exponential moment-generating function* (see [7]) of T_0. Let $\boldsymbol{\pi_{spt}}$ be the steady-state spatial distribution of the mobility model and let $N_{\mathbf{x}}$ be the set of mobility states at which a node A can potentially form a link with a node B in state $\mathbf{x}$. Then, the parameter $\alpha(n)$ is given by

$$\alpha(n) = \frac{\alpha_0(n)}{\frac{n+1}{n}\alpha_0(n)\beta_c + (1-\beta_c)},$$

where $\alpha_0(n) = 1 - EGF_{T_0}\left\{\log(1-E[T_\infty]^{-1})^n\right\}$ and

$$1-\beta_c = \left(1-\frac{1}{E[T_0]}\right)\sum_{k=0}^{n-1}\sum_{\mathbf{x}}\frac{\pi_{spt}(\mathbf{x})}{k+1}\binom{n-1}{k}\pi_{spt}^k(N_{\mathbf{x}}) \times \{1-\pi_{spt}(N_{\mathbf{x}})\}^{n-1-k}.$$

Due to page limitations, we skip the proof for the above. It follows in similar lines as the corresponding theorem in [7]

This completes the construction of the collapsed chain Γ_v. In order to complete the analysis, one needs to determine the steady-state probabilities of all the states in this chain. This is done by solving the equations (1)-(5). However, we note that the steady-state equations for the R-states (5) are non-linear. Hence, it is impossible to obtain closed-form solutions for the throughput. Nevertheless, (1)-(5) can be solved by iterative methods. In general, this queuing-theoretic model converges within 10-20 iterations. In contrast, simulating the exact network for a given n takes a few million epochs for the system to reach steady-state. In addition, the entire simulation has to be repeated in order to understand scalability issues, effects of various parameters, etc.

Having obtained the steady-state distribution of Γ_v thus, we can compute the throughput (in blocks per epoch) contributed by all the n relay nodes for multihop unicast as follows:

Theorem 3: The steady-state throughput achieved for the stochastic ICMANET model by the multihop protocol with back-pressure-based buffer management policy is given as:

$$\mathcal{C}_{s,d} = \frac{1}{E[T_0]} + \frac{n(1-\beta_c)}{E[T_0]}\frac{\sum_{j=0}^{B-1}\pi(D_j)}{\pi(E)+\sum_{j=0}^{B-1}\pi(D_j)}. \tag{6}$$

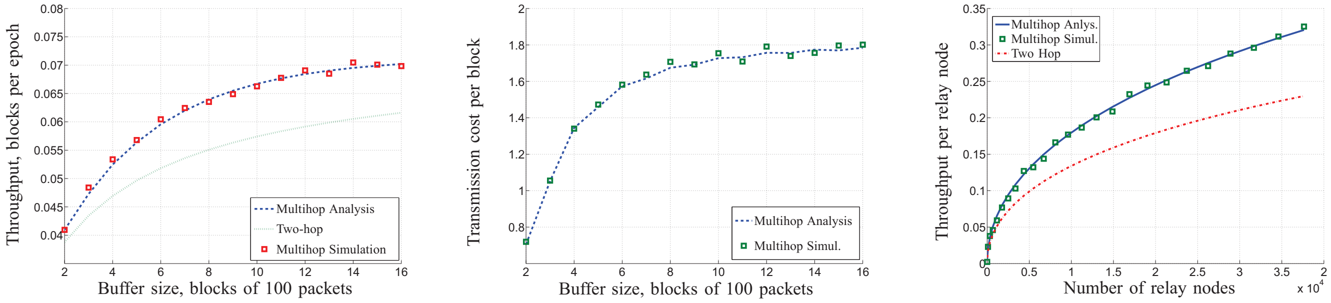
Further, the steady-state transmission overhead compared to two-hop routing is given by:

$$\mathcal{T}_{s,d} = \frac{\sum_{j=0}^{B}\sum_{j'=0}^{j-2}\pi(R_{j,j'})}{\sum_{j=0}^{B-1}\pi(D_j)}. \tag{7}$$

The expression for throughput and transmission overhead follows from the fact that the throughput is given by the ratio of the total steady-state probability of the "desirable" states (in Γ_v, these are the D-states) to the total steady-state probability of all states where the destination node is linked with (i.e., E- and D-states), times the frequency of establishing a link with the destination which can be computed as $\frac{(1-\beta_c)}{E[T_0]}$. The first term in the throughput indicates the contribution of direct source-to-destination contacts. As we shall see in the discussion of results, multihop relaying offers higher throughput than the corresponding two-hop protocol under the same network setup. However, it comes at the price of higher energy spent due to additional relay-to-relay transmissions. The above theorem shows also that this trade-off can also be quantified using our framework.

IV. Simulation Results and Discussion

Our first verification was using the random-walk-on-grid model. Here, nodes perform a discrete random walk on a $M \times M$



(a) (b) (c)

Fig. 2: Simulation Results for the Random-Walk-on-Grid (a and b) and RRWP (c) mobility models

square grid of cells. In order to study the effect of finite buffers on the throughput of multihop routing vs two-hop routing, we simulated an ICMANET network in MATLAB, consisting of 30 nodes on a 25×25 grid with a communication radius of $K = 2$ grid points. For buffer sizes ranging from $B = 2$ to $B = 16$ blocks of 100 packets each per node, we plotted the observed throughput in Fig. 2(a). In addition, the corresponding plots for the transmission cost incurred have also been plotted in Fig. 2(b). We have also plotted the same obtained using our iterative queuing-theoretic framework. In addition, the throughput for two-hop routing under the same conditions is also shown in the figure, using the analysis developed in [7]. Clearly, multihop routing gives a consistent gain in the throughput vis-a-vis two-hop routing. We then use a restricted version of the random-waypoint mobility model (RRWP) in our second set of simulations, where we studied the effects of contention and node density on throughput. Under this model, nodes exhibit random-waypoint mobility in one of several restricted areas for most of the time. Occasionally however, with a certain small probability, they also choose a waypoint in a different area and move on. The node velocity was chosen from a uniform random distribution, with $v_{min} = 3\ m/s$ and $v_{max} = 10\ m/s$. The communication range was chosen to be $250\ m$. The pause-time was modeled as an exponential distribution with a mean of $60\ s$. The probability of transition to a different area was 0.05. In Fig. 2(c), the per-node throughput contribution in the network is plotted as a function of the number of nodes, for a square region of a fixed area of $100km^2$. The total throughput grows sub-linearly with n as a result of contention and saturates at a certain value. Generally, it is observed that with increase in contention between nodes, the buffer-occupancy distribution during links with the destination shift away from the empty state. Improvement in throughput due to this slight mitigation is however diminished considerably since the probability of establishing a link itself goes down under heavy contention, since the term $1 - \beta_c$ dominates in (6).

V. Conclusions

The achievable throughput in an ICMANET under a class of multihop single-copy unicast protocols were analyzed in this paper. The analysis developed here studied the performance of these networks under steady-state mobility. A novel generalized iterative queuing-theoretic framework was presented, exploiting the idea of embedded Markov-chains and capturing the effects of finite buffers, contention, and interference. The accuracy of the analysis was validated by simulations of the network model in real time. The merit of the proposed framework is that it is valid for generalized stochastic mobility models with arbitrary complexity. In addition, it provides us a way to determine how mobility and buffer size impacts the performance of various routing protocols (e.g., multihop versus two-hop routing), which is very critical in the practical design of ICMANETs.

VI. Acknowledgements

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