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Probing-Based Two-Hop Relay with Limited Packet Redundancy

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***Abstract*—Due to their simplicity and efficiency, the two-hop relay algorithm and its variants serve as a class of attractive routing schemes for mobile ad hoc networks (MANETs). With the available two-hop relay schemes, a node, whenever getting an opportunity for transmission, randomly probes only once a neighbor node for the possible transmission. It is notable that such single probing strategy, although simple, may result in a significant waste of the precious transmission opportunities in highly dynamic MANETs. To alleviate such limitation for a more efficient utilization of limited wireless bandwidth, this paper explores a more general probing-based two-hop relay algorithm with limited packet redundancy. In such an algorithm with probing round limit τ and packet redundancy limit f, each transmitter node is allowed to conduct up to τ rounds of probing for identifying a possible receiver and each packet can be delivered to at most f distinct relays. A general theoretical framework is further developed to help us understand that under different setting of τ and f, how we can benefit from multiple probings in terms of the per node throughput capacity.**

I. INTRODUCTION

The two-hop relay algorithm, since first proposed in [1], has attracted great research interests in the field of mobile ad hoc networks (MANETs). In the two-hop relay routing, a packet reaches its destination either through a direct transmission from the source or by two-hop transmissions via an intermediate relay node, which first receives the packet from the source and then forwards it to the destination. Therefore, each packet travels at most two hops to reach the destination.

Due to its efficiency and simplicity, the two-hop relay algorithm and its variants have become a class of popular routing schemes being intensively studied in literature. The algorithms in [1]–[3] can be regarded as the out-of-order routing without packet redundancy, where a packet has at most one copy and will be accepted by its destination as long as it has never been received before. The two-hop relays in [4], [5] also adopt the out-of-order reception but multiple redundant copies can be distributed for each packet. Later, some new two-hop relay algorithms with in-order reception have been proposed in [6], [7] where each packet has a fixed number of copies (i.e., with exact redundancy). The two-hop relay schemes in [8], [9] also belongs to the line of in-order reception but each packet is allowed to have a limited number of copies (i.e., with limited redundancy). More recently, a general group-based two-hop relay with limited redundancy was also proposed in [10], where each packet is delivered to a limited number of relay nodes and can be accepted by its destination if it is among the group of packets the destination is currently requesting.

Notice that in the available two-hop relay schemes with packet redundancy (fixed or limited), no matter adopting out-of-order reception, in-order reception or group-based reception, a node, whenever getting an opportunity for transmission, randomly probes only once a neighbor node for possible transmission if its destination node is not within its transmission range. Such single probing strategy, although simple, may result in a significant waste of the precious transmission opportunities in highly dynamic MANETs. For example, for the case that the transmitter node regards a randomly probed neighbor node as a relay and hopes to deliver a redundant packet copy to it, it may happen that the relay is already carrying such a copy for that packet; on the other hand, for the case that the transmitter node acts as a relay and hopes to forward a packet to the randomly probed node, this node may have already received all the packets carried by the transmitter. Thus, when a wrong node is selected through such single probing strategy, no transmission can be conducted successfully in the above two cases and the transmission opportunity of the transmitter node will be wasted.

To alleviate the limitation of single probing for a more efficient utilization of wireless bandwidth, this paper proposes a general probing-based two-hop relay with limited packet redundancy. Our main contributions are as follows.

- We propose in Section II a two-hop relay with probing round limit τ and packet redundancy limit f (2HR-(τ, f) for short), here each transmitter node is allowed to conduct up to τ rounds of probing for identifying a possible receiver and each packet can be delivered to at most f distinct relays. This algorithm covers available two-hop routing protocols [6]–[9] as special cases ($\tau = 1$).
- In Section III, we further develop a general theoretical framework to characterize the complicated packet delivery process under the 2HR-(τ, f), where the finite-state absorbing Markov chain technique is adopted to model the packet dispatching process at the source and the packet receiving process at the destination. By setting $\tau = 1$, our framework reduces to some available models developed for two-hop relay [8], [9].
- With the help of the theoretical framework, closed-form

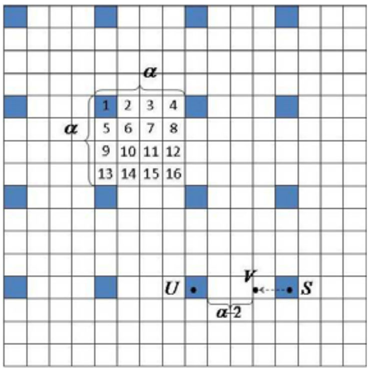


Fig. 1. Illustration of cells in a transmission-group with $m = 16$ and $\alpha = 4$.

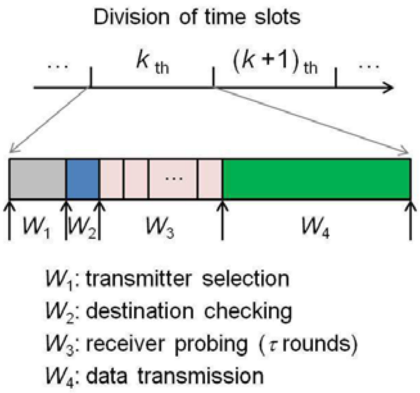


Fig. 2. Partition of a time slot.

expressions are developed for the per node throughput capacity. Extensive simulation and theoretical results are also provided in Section IV to validate the efficiency of the new relay algorithm and corresponding theoretical framework.

II. Routing Algorithm

A. System models

Similar to [11], we consider in this paper a torus of unit area which is evenly divided into $m \times m$ cells, as shown in Fig. 1. Time is slotted, and there are n nodes roaming around in the torus from cell to cell according to the i.i.d. mobility model [6], [8]. Each node employs a common transmission range r, and the protocol model [12] with guard factor Δ is adopted here to account for interference issues. The transmission-group based scheduling scheme [13] is adopted here as the MAC scheme to schedule simultaneous link transmissions. A whole time slot is allocated only for data transmissions in one-hop range and for any node pair, the data bits that can be successfully transmitted from the transmitter to the receiver is normalized to one packet here. We consider the permutation traffic pattern widely adopted in previous studies [1], where there are in total n distinct traffic flows (one corresponds to one source-destination pair). Under such traffic pattern, each node is not only the source of its locally generated traffic flow but also the destination of another traffic flow originated from some other node. The traffic flow generated at each node is assumed to have an average input rate λ (packets/slot).

Now we proceed to introduce the partition of a time slot. As shown in Fig. 2, each time slot is divided into four subslots. In subslot W_1, all nodes in an active cell contend to become the transmitter in a DCF way, where each node there randomly selects a back-off counter from $(0, W_1]$ and the node whose counter is the first to become zero broadcasts a message claiming itself as the transmitter. Subslot W_2 is specified for destination checking where the destination node of the flow originated from the transmitter will reply to the transmitter if it is inside the one-hop neighborhood. Otherwise, if no reply is heard from the destination, in subslot W_3 the transmitter will conduct at most τ rounds of probing until an eligible receiver is selected (in each probing round, a neighboring node is randomly selected as the receiver). Subslot W_4 is reserved for data transmission from the transmitter to the selected receiver. If no eligible receiver is selected in subslot W_3 (and thus no packet can be transmitted), the transmitter stays idle in W_4.

B. 2HR-(τ, f) Routing Algorithm

Now we are ready to introduce the general probing-based two-hop relay algorithm 2HR-(τ, f). Under such an algorithm, each transmitter will conduct at most τ rounds of probing to select an eligible receiver when its destination node is not inside the one-hop neighborhood, and at most f copies will be distributed out for each packet.

Notice that under the permutation traffic pattern considered in this paper, there are in total n distinct flows and each node can be a potential relay for other $n-2$ flows (excluding the two flows originated from and destined for itself). We assume that each node maintains in its buffer n individual FIFO queues: one local-queue storing the locally generated packets, one already-sent-queue storing the packets whose f copies have been distributed but the reception status are not confirmed yet, and $n-2$ relay-queues storing packets from other $n-2$ flows (one for each flow). For throughput capacity analysis, we assume all queues have enough buffer space such that no packet overflow will happen.

Without loss of generality, we focus on a tagged flow and denote by S the source node and denote by D the destination node. S labels each locally generated packet P with a *sequence number* $SN(P)$ and D maintains a *request number* $RN(D)$ to indicate the sequence number of the packet for which it is currently requesting. Every time S is selected as the transmitter in an active cell, it executes the following Algorithm 1.

III. Theoretical Analysis

A. Some Basic Probabilities

Lemma 1: Consider a MANET adopting the 2HR-(τ, f) routing algorithm. For a given time slot and the tagged flow, if we use p_1 to denote the probability that S conducts a source-to-destination transmission and use p_2 to denote the

Algorithm 1 2HR-(τ, f) routing algorithm

S checks whether its destination D is in the one-hop neighborhood;
if D is within the one-hop neighborhood of S **then**
  S executes Procedure 1;
else
  With probability $1/2$, S randomly selects to do source-to-relay transmission or relay-to-destination transmission;
  if S selects source-to-relay transmission **then**
    S executes Procedure 2;
  else
    S executes Procedure 3;
  end if
end if

Procedure 1 source-to-destination transmission

S obtains from D the request number $RN(D)$;
S directly sends to D the packet P with sequence number $SN(P) = RN(D)$;
S deletes all packets with sequence number less than $RN(D)$ from both local-queue and already-sent-queue;
S moves ahead the remaining packets in local-queue and already-sent-queue;

Procedure 2 source-to-relay transmission

$i \leftarrow 1$;
while $i \leq \tau$ **do**
  S randomly selects a node (say V_i) out of the one-hop neighbors;
  S checks whether its head-of-line (HoL) packet P_h is carried by V_i;
  if V_i doesn't carry P_h **then**
    S delivers to V_i a copy of P_h;
    if All f copies of P_h have been distributed **then**
      S puts P_h into the end of the already-sent-queue;
      S moves ahead the remaining packets behind P_h in the local-queue;
    end if
    $i \leftarrow \tau + 1$;
  end if
  $i \leftarrow i + 1$;
end while

probability that S conducts a source-to-relay or relay-to-destination transmission, then we have

$$p_1 = \frac{1}{\alpha^2}\left\{\frac{9n - m^2}{n(n-1)} - \left(\frac{m^2-1}{m^2}\right)^{n-1}\frac{8n+1-m^2}{n(n-1)}\right\} \tag{1}$$

$$p_2 = \frac{1}{\alpha^2}\left\{\frac{m^2-9}{n-1}\left(1 - \left(\frac{m^2-1}{m^2}\right)^{n-1}\right) - \left(\frac{m^2-9}{m^2}\right)^{n-1}\right\} \tag{2}$$

According to Procedure 2 of the 2HR-(τ, f) routing algorithm, we can see that when S decides to conduct the source-to-relay transmission, it will independently conduct at most τ rounds of probing (in each probing round, a neighboring node is randomly selected as the receiver) to deliver out a copy for its HoL packet P_h. Then we have the following lemma.

Lemma 2: In a MANET with 2HR-(τ, f) routing algorithm, for a given time slot and the tagged flow, suppose S is delivering copies for the HoL packet P_h, and there are already j copies of P_h in the network, $1 \leq j \leq f$. If we denote by $P_d(j)$ the probability that S successfully delivers a new copy of P_h to some relay node in the time slot, then we have

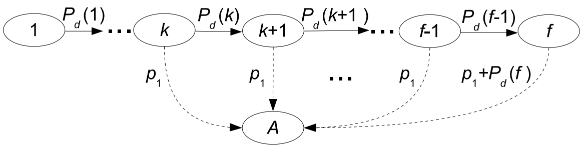
$$P_d(j) = \frac{(m^2-9)^{n-1}}{2\alpha^2 m^{2n-2}}\left\{\sum_{s=1}^{n-j-1}\sum_{t=0}^{j-1}\sum_{k=0}^{s+t}\binom{n-j-1}{s}\binom{j-1}{t}\binom{s+t}{k}\frac{8^{s+t-k}}{(m^2-9)^{s+t}}\cdot\frac{1}{k+1}\cdot\left(1-\left(\frac{t}{t+s}\right)^{\tau}\right)\right\} \tag{3}$$

Procedure 3 relay-to-destination transmission

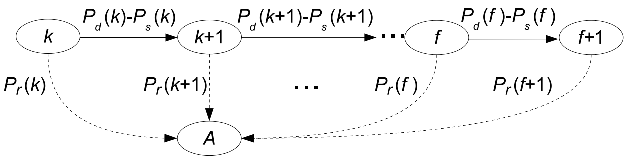
$i \leftarrow 1$;
while $i \leq \tau$ **do**
  S randomly selects a node (say V_i) out of the one-hop neighbors;
  S obtains from V_i the request number $RN(V_i)$;
  S checks whether it carries a packet P with $SN(P) = RN(V_i)$;
  if S carries such packet P **then**
    S sends P to node V_i;
    S deletes all packets with sequence number less than $RN(V_i)$ from its relay-queue specified for V_i;
    S moves ahead the remaining packets in the relay-queue specified for V_i;
    $i \leftarrow \tau + 1$;
  end if
  $i \leftarrow i + 1$;
end while

Now we proceed to explore the probability that D may receive a packet for which it is requesting in Procedure 3. Consider some relay node R carrying a packet P with $SN(P) = RN(D)$. For a time slot, suppose R is selected as the transmitter and R decides to conduct the relay-to-destination transmission. It is easy to see that R will deliver to D the packet P if and only if the following two events happen simultaneously: D is selected as the receiver in the t_{th} round of probing, $1 \leq t \leq \tau$; for the node V_i selected in the i_{th} round of probing, $1 \leq i < t$, $V_i \neq D$, R does not carry any packet $P^{'}$ with $SN(P^{'}) = RN(V_i)$. Without loss of generality, we denote by p_{nc} the probability that R does not carry any packet $P^{'}$ with $SN(P^{'}) = RN(V_i)$, $1 \leq i < t$, then we have the following lemma.

Lemma 3: In a MANET with 2HR-(τ, f) routing algorithm, for a given time slot and the tagged flow, suppose D is requesting for packet P, i.e., $SN(P) = RN(D)$, and there are



(a) Absorbing Markov chain for the packet dispatching process at the source node S.



(b) Absorbing Markov chain for the packet receiving process at the destination node D.

Fig. 3. Absorbing Markov chain for a packet P of the tagged flow, given that the destination node D starts to request for P when there are already k copies of P in the network. For each transient state, the transition back to itself is not shown for simplicity.

already j copies of packet P in the network, $1 \leq j \leq f+1$. If we denote by $P_r(j)$ the probability that D successfully receives P in the time slot, then we have

$$P_r(j) = p_1 + \frac{(j-1)(m^2-9)^{n-2}}{2\alpha^2(n^2-3n+2)m^{2n-2}} \cdot \sum_{k=0}^{n-3} \binom{n-1}{k+2} \frac{1-(\frac{k}{k+1}p_{nc})^\tau}{1-\frac{k}{k+1}p_{nc}} \cdot \frac{9^{k+2}-8^{k+2}}{(m^2-9)^k} \quad (4)$$

B. Service Times at the Source S and the Destination D

Definition 1: For a general packet P of the tagged flow, its service time at the source S is defined as the time elapsed between the time slot when S starts to deliver copies for P and the time slot when S stops distributing copies for P; the service time at the destination D is defined as the time elapsed between the time slot when D starts to request for P and the time slot when D receives P.

For a time slot and a general packet P of the tagged flow, suppose that there are already k copies of P (including the original one at the source node S) in the network when the destination node D starts to request for P, $1 \leq k \leq f+1$. If we denote by $P_s(k)$ the probability of simultaneous source-to-relay transmission (from S to some node without P) and relay-to-destination transmission (from some relay carrying P to D), we can see that for the packet P, the dispatching process at S and the receiving process at D can be modeled by two finite-state absorbing Markov chains shown in Fig. 3a and 3b, respectively, where the absorbing state A denotes the termination of the service process.

Given there are already k copies of P in the network when D starts to request for P, if we denote by $X_S(k)$ and $X_D(k)$ the service times at S and at D, respectively, it is easy to see that $X_S(k)$ (resp. $X_D(k)$) corresponds to the time it takes the Markov chain in Fig. 3a (resp. in Fig. 3b) to become absorbed given that the chain starts from state 1 (resp. state k).

Lemma 4: In a MANET with 2HR-(τ, f) routing algorithm, for a general packet P of the tagged flow, suppose that there are already k copies of P in the network when D starts to request for P, then the expected service times $\mathbb{E}\{X_S(k)\}$ and $\mathbb{E}\{X_D(k)\}$ can be determined as

$$\mathbb{E}\{X_S(k)\} = \begin{cases} \sum_{i=1}^{k-1} \frac{1}{P_d(i)} + \frac{1}{p_1+P_d(k)} \\ \quad \cdot \left(1+\sum_{j=1}^{f-k} \phi_1(k,j)\right) & \text{if } 1 \leq k \leq f, \\ \sum_{i=1}^{f} \frac{1}{P_d(i)} & \text{if } k = f+1. \end{cases} \quad (5)$$

$$\mathbb{E}\{X_D(k)\} = \begin{cases} \frac{1}{P_r(k)+P_d(k)-P_s(k)} \Big(1+\sum_{j=1}^{f-k} \phi_2(k,j) \\ \quad + \frac{P_d(f)-P_s(f)}{P_r(f+1)} \phi_2(k, f-k)\Big) & \text{if } 1 \leq k \leq f-1, \\ \frac{1}{P_r(f)+P_d(f)-P_s(f)} \left(1+\frac{P_d(f)-P_s(f)}{P_r(f+1)}\right) & \text{if } k = f, \\ \frac{1}{P_r(f+1)} & \text{if } k = f+1. \end{cases} \quad (6)$$

where

$$\phi_1(k,j) = \prod_{t=1}^{j} \frac{P_d(k+t-1)}{p_1+P_d(k+t)}$$

$$\phi_2(k,j) = \prod_{t=1}^{j} \frac{P_d(k+t-1)-P_s(k+t-1)}{P_r(k+t)+P_d(k+t)-P_s(k+t)}$$

C. Throughput Capacity of 2HR-(τ, f)

Lemma 5: For the 2HR-(τ, f) routing algorithm, we have

$$\mathbb{E}\{X_S(f+1)\} \leq \mathbb{E}\{X_D(f+1)\}, 1 \leq f \leq n-2, 1 \leq \tau \leq \tau_0 \quad (7)$$

where τ_0 is given by

$$\tau_0 = \left\lfloor \frac{(n-f-1)p_2 - 2(n-2)f \cdot p_1}{f^2 \cdot p_2} \right\rfloor \quad (8)$$

The proofs for Lemmas 1, 2, 3, 4 and 5 are omitted here due to space limit. Please kindly refer to [14] for details.

Theorem 1: In a cell partitioned MANET where nodes move according to the i.i.d. mobility model and the 2HR-(τ, f) is adopted for packet routing, if we denote by μ the per-node throughput capacity, i.e., the network can stably support any traffic input rate $\lambda (\lambda < \mu)$, then for any given f and τ, $1 \leq f \leq n-2$, $1 \leq \tau \leq \tau_0$, the per-node throughput capacity μ can be determined as

$$\mu = p_1 + \frac{f \cdot (m^2-9)^{n-2}}{2\alpha^2(n^2-3n+2)m^{2n-2}} \sum_{k=0}^{n-3} \binom{n-1}{k+2} \cdot \frac{9^{k+2}-8^{k+2}}{(m^2-9)^k} \cdot \frac{(k+1)^\tau (n-2)^\tau - k^\tau (n-2-f)^\tau}{(n-2)^{\tau-1}(k+1)^{\tau-1}(n-2+kf)} \quad (9)$$

Proof: From Lemma 5 and Theorem 1 in [8], we can see that for any given f and τ, $1 \leq f \leq n-2$, $1 \leq \tau \leq \tau_0$, the per node throughput capacity μ is determined as

$$\mu = \frac{1}{\mathbb{E}\{X_D(f+1)\}} = P_r(f+1) \quad (10)$$

combining with (4), we can see that in order to derive the throughput capacity μ, the only remaining issue is to derive the probability p_{nc}.

It is noticed that according to Theorem 1 in [9], for a general packet P of the tagged flow, as the input traffic rate approaches the throughput capacity, i.e., $\lambda \to \mu$, the destination node D will start to request for P only after the source node S has already distributed out all f copies for P. If we denote by $P_{req}(j)$ the probability that there are already j copies of P when D starts to request for P, $1 \leq j \leq f+1$, then we have

$$\lim_{\lambda \to \mu} P_{req}(f+1) = 1 \tag{11}$$

i.e., as $\lambda \to \mu$ D will start to request for each packet of the tagged flow after the packet has already $f+1$ copies in the network.

For a time slot, suppose some node R which carries a packet P with $SN(P) = RN(D)$, decides to conduct the relay-to-destination transmission. Without loss of generality, we assume D is selected as the receiver in the t_{th} round of probing, $1 \leq t \leq \tau$, and denote by V_i the node selected in the i_{th} round of probing, $1 \leq i < t$, $V_i \neq D$. From (11), it is easy to see that the probability that R does not carry any packet $P^{'}$ with $SN(P^{'}) = RN(V_i)$ $(1 \leq i < t)$, i.e., the probability p_{nc}, can be given by

$$p_{nc} = \frac{n-2-f}{n-2} \tag{12}$$

together with (10) and (4), it follows (9). Then we complete the proof for Theorem 1. ■

IV. Numerical Results

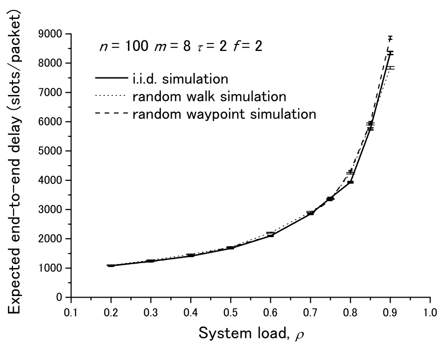
A. Simulation Settings

A dedicated C++ simulator was developed to simulate the packet delivery process of the proposed 2HR-(τ, f) routing algorithm, which is now available on-line at [15]. Similar to [16] the guard factor Δ was fixed as $\Delta = 1$. The traffic flow locally generated at each source node was assumed to be a Poisson stream with input rate λ (packets/slot). Besides the i.i.d. mobility model, we also implemented the random walk and random waypoint mobility models to simulate the node movement in a MANET [17], [18].

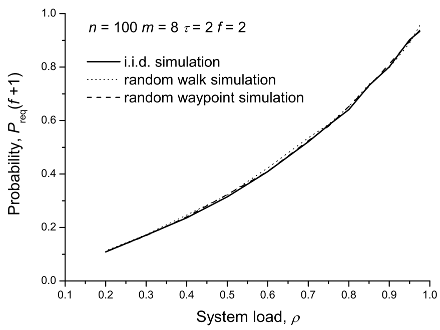
B. Theoretical Model Validation

Extensive simulations were conducted to verify our theoretical models. Here only the simulation results under the setting of $(n = 100, m = 8)$ were presented, and the simulation results of other network scenarios can also be obtained by our simulator [15]. The parameters τ and f were fixed as $\tau = 2$ and $f = 2$, respectively, where the per node throughput capacity was determined as $\mu = 1.21 \times 10^{-3}$(packets/slot). The corresponding simulation results were summarized in Fig. 4. Notice that all the simulation results of the expected end-to-end delay were reported with the 95% confidence intervals.

Figs. 4a and 4b indicate clearly that our theoretical model could nicely capture the throughput capacity behavior of MANETs with 2HR-(τ, f) routing algorithm. Specifically, one



(a) Expected end-to-end delay vs. system load ρ.



(b) Probability $P_{\text{req}}(f+1)$ vs. system load ρ.

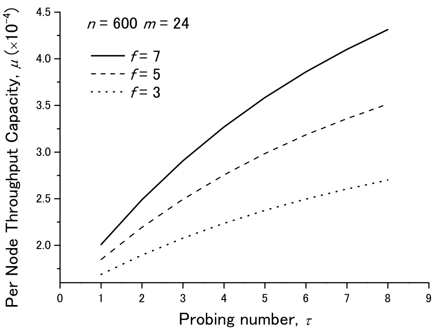
Fig. 4. Theoretical model validation under the network setting of $(n = 100, m = 8, \tau = 2, f = 2)$ with a per node throughput capacity of $\mu = 1.21 \times 10^{-3}$(packets/slot).

can easily observe from Fig. 4a that, the simulated expected end-to-end delay gradually increases as the system load ρ increases, and becomes extremely sensitive to the variations of ρ as ρ approaches 1. Such skyrocketing behavior of expected end-to-end delay can also serve as an intuitive validation for the throughput capacity derived by our theoretical model. Recall that $P_{req}(f+1)$ denotes the probability that there are already $f+1$ copies of a packet P in the network when its destination node starts to request for it. Fig. 4b shows clearly that as ρ approaches 1, i.e., $\lambda \to \mu$, we have $P_{req}(f+1) \to 1$, which proves (11) and in turn validates the throughput capacity results derived in Theorem 1.

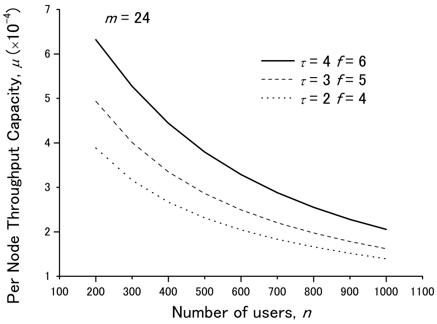
It is interesting to observe from Figs. 4a and 4b that for the network scenario there, the expected end-to-end delay and $P_{req}(f+1)$ of the 2HR-(τ, f) under the random walk and random waypoint mobility models exhibit very similar behaviors with that under the i.i.d. mobility model. Therefore, our theoretical models, although developed under the i.i.d. model, can also nicely capture the network throughput capacity behaviors under the random walk and random waypoint mobility models.

C. 2HR-(τ, f) Throughput Capacity Analysis

Based on the theoretical framework developed for per node throughput capacity, we now proceed to explore the throughput



(a) μ vs. τ.



(b) μ vs. n.

Fig. 5. Per node throughput capacity μ vs. probing limit τ and number of users n.

capacity performances of the 2HR-(τ, f) routing algorithm and its relationship with the probing limit τ and the number of users n. Fig. 5a shows clearly that for each setting of f there, multiple probings can significantly improve the per node throughput capacity μ. For example, for the setting of $f = 7$, the throughput capacity μ of $\tau = 3$ (resp. $\tau = 7$) is 2.9×10^{-4} (resp. 4.1×10^{-4}) (packets/slot), which is almost 1.45 (resp. 2.05) times that of $\tau = 1$ (2.0×10^{-4} (packets/slot)). One can easily observe from Fig. 5b that for each (τ, f) setting there, the per node throughput capacity μ vanishes quickly as the number of users n (the node density n/m^2) increases. Actually, such behavior can be explained as follows: for the given (τ, f) setting, the throughput capacity μ derived in (10) is limited by $P_r(f+1)$, which decreases as the node density increases.

V. Conclusion and Future Work

This paper proposed a general 2HR-(τ, f) routing algorithm for efficient utilization of wireless resources in MANETs. A Markov chain theoretical framework was further developed to model the performance of the new relay algorithm, based on which closed-form expressions were derived for the per-node throughput capacity. Extensive simulation and theoretical studies indicate that the theoretical framework is very efficient in performance modeling for the 2HR-(τ, f) algorithm, and the new relay algorithm can significantly improve the per node throughput capacity by enabling more rounds of receiver probing. It is interesting to notice that our theoretical throughput capacity model, although was developed under the i.i.d. mobility model, can also be used to nicely capture the network behaviors under the random walk and the random waypoint models as well.

Notice that the theoretical framework and throughput capacity results in this paper were developed based on the assumption that the queue buffer at each node is large enough with no packet overflow and the simple policy that in Algorithm 1 Procedure 2 and Procedure 3 will be conducted with equal probability. Therefore, one of our future research directions is to explore the impact of such policy and the queue buffer size on the throughput capacity performance of the proposed 2HR-(τ, f) algorithm.

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