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Capacity vs. Delivery Delay in MANETs with Power Control and f-cast Relay

Jiajia Liu
Tohoku University
Sendai, Japan 980-8579
Email: liu-jia@it.ecei.tohoku.ac.jp

Xiaohong Jiang
Future University Hakodate
Hokkaido, Japan 041-8655
Email: jiang@fun.ac.jp

Hiroki Nishiyama and Nei Kato
Tohoku University
Sendai, Japan 980-8579
Email: {bigtree,kato}@it.ecei.tohoku.ac.jp

***Abstract*—A lot of works have been dedicated towards understanding the relationship between throughput capacity and packet delay in mobile ad hoc networks (MANETs). However, nearly all these works either assume a localized transmission range, or report the relationship between throughput capacity and packet delay only in terms of the number of users. It remains largely unknown for such a fundamental relationship in terms of other network parameters, like the packet redundancy and node transmission range. As a first step towards this end, in this paper we derive closed-from expressions for throughput capacity and delivery delay under a general setting of node transmission range and also a generalized two-hop relay with limited packet redundancy. Extensive numerical results are further provided to explore how throughput capacity varies with delivery delay in terms of various network parameters, such as the number of users, the packet redundancy limit, and the node transmission range, etc.**

I. Introduction

Mobile ad hoc network (MANET) is a fully self-autonomous system where mobile nodes freely communicate with each other via wireless channels [1], [2]. Since it can be rapidly deployed, extended and reconfigured at very low cost, the MANET is believed to be one of the most important components among next generation networks. Therefore, it is a critical issue to thoroughly understand the performances of such networks [3].

So far, a lot of works have been done to explore the relationship between throughput capacity and packet delay in MANETs under various mobility models. Lin *et al.* [4] studied the independent and identically distributed (i.i.d.) model, and showed that the capacity λ and delay $\mathbf{D}$ there have a relationship of $\lambda = O(\sqrt[3]{\mathbf{D}/n}\log n)$, where n is the number of users. Later, Neely *et al.* [5] also studied the i.i.d. model and showed that $\mathbf{D}/\lambda \geq O(n)$ by allowing multiple copies for each packet. Gamal *et al.* [6] showed that under the random walk mobility, $\mathbf{D} = \Theta(n\lambda)$ for $\lambda = O(1/\sqrt{n\log n})$, and $\mathbf{D} = \Theta(n\log n)$ for $\lambda = \Omega(1/\sqrt{n\log n})$. Sharma *et al.* [7] showed that when nodes move according to the random waypoint model on a unit sphere, $\mathbf{D}/\lambda \geq \Theta(nT_p)$ where T_p is the packet duration. More recently, Ying *et al.* [8] has examined the optimal delay-throughput trade-offs under both fast and slow mobility time-scales.

However, nearly all these works either assume a localized transmission range ($i.e., r = \Theta(1/\sqrt{n})$), or consider the basic two-hop relay routing (or its variants) [9], or report the order sense scaling laws and thus the relationship between throughput capacity and packet delay only in terms of the number of users. It remains largely unknown that how throughput capacity varies with packet delay in other network parameters, like the packet redundancy and node transmission range.

As a first step towards this end, in this paper, we analytically study the relationship between throughput capacity and delivery delay in mobile ad hoc networks under a general setting of node transmission range and also a generalized two-hop relay routing with f-cast (2HR-f). Under such a routing scheme, each packet is delivered to at most f distinct relay nodes and should be received in order at its destination.

The main contributions of this paper are summarized as follows:

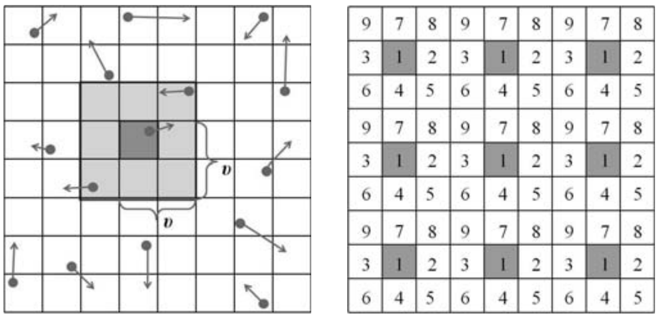
- After assuming nodes move according to the i.i.d. mobility model and each contends for wireless channel according to a transmission-group based medium access control (MAC) scheme, we derive closed-form expressions for throughput capacity and delivery delay in such a MANET.
- Extensive numerical results are provided to explore the relationship between throughput capacity and delivery delay in terms of various network parameters, such as the number of users, the packet redundancy limit, and the node transmission range, etc.

The remainder of this paper is outlined as follows. In Section II, we introduce the system assumptions, a transmission-group based MAC scheme and the 2HR-f routing scheme. In Section III, we derive closed-form expressions for the throughput capacity and delivery delay. We explore the relationship between throughput capacity and delivery delay in Section IV, and finally conclude the paper in Section V.

II. Preliminaries

A. System Models

Similar to [10], the network considered in this paper is assumed to be a unit torus which is divided into $m \times m$ equal cells. Time is slotted (and each slot is of fixed length) and during any time slot a successful transmission conveys a fixed amount of data (normalized to a "packet", henceforth). We consider a general setting of transmission range, as shown in Fig. 1a, each node can transmit to a set of cells which



(a) Cell partitioned network. (b) Illustration of transmission-groups with $\alpha = 3$.

Fig. 1. Network cell partition and transmission-group.

have horizontal and vertical distances of no more than $\upsilon - 1$ ($1 \leq \upsilon \leq \lfloor \frac{m+1}{2} \rfloor$) cells away from its current cell [11], [12].

We assume that there are n mobile nodes randomly and independently moving among these m^2 cells according to the i.i.d. mobility model [5]. Each node has a locally generated traffic flow to deliver to some node, and also needs to receive another traffic flow originated from some other node [13]. Under such a permutation traffic pattern, there are in total n flows inside the network.

The protocol model introduced in [14] is adopted here as interference model. Suppose node i is transmitting to node j. According to the interference model, the transmission from node i to node j is successful if and only if that, for any other node k that is transmitting simultaneously with node i, we have

$$|X(k) - X(j)| \geq (1 + \Delta)|X(i) - X(j)|$$

where Δ is a fixed positive constant representing the guard zone in the protocol model [14], and $X(\cdot)$ denotes the physical node location.

B. A Transmission-group Based MAC Scheme

Since under the general setting of transmission range, a node in some cell can transmit to other cells which have relative horizontal and vertical distances of no more than $\upsilon - 1$ cells. According to the interference model, only cells that are sufficiently far away (depending on Δ) could support simultaneous transmissions without interfering with each other.

In order to support as many simultaneous transmissions as possible, we adopt here a transmission-group based MAC scheme [15], [16]. First we give the definition of a transmission-group.

transmission-group: a transmission-group is defined as a subset of cells, where any two of them have a vertical and horizontal distance of some multiple of α cells away and all the cells there could transmit simultaneously without interfering with each other. As shown in Fig. 1b with $\alpha = 3$, there are in total 9 transmission-groups.

Given the guard factor Δ, the parameter α should be set accordingly to ensure the successful simultaneous transmissions among cells of a transmission-group. After applying some derivations similar to that in [12], the parameter α can be determined as follows

$$\alpha = \min\{\upsilon + \lceil \sqrt{2(\Delta + 1)^2 \upsilon^2 - (\upsilon - 1)^2} \rceil, m\} \qquad (1)$$

Notice that there are only α^2 transmission-groups, and each cell belongs to an individual transmission-group. If transmission-groups become active (i.e., get transmission opportunity) alternatively, then each cell become active in every α^2 time slots. If there are more than one nodes inside an active cell, a transmitting node is selected randomly from them in a distributed way according to the method introduced in [16]. The selected node then follows the 2HR-f routing scheme for packet transmission.

C. The 2HR-f Routing Scheme

The generalized two-hop relay with f-cast (2HR-f) is adopted here for packet transmission [5], [16], [17], $1 \leq f \leq n - 2$. Under such a routing scheme, each destination node receives packets according to their sequence numbers, and each packet at its source node may be delivered to at most f distinct relay nodes. Therefore, together with the original one at its source source, each packet may have at most $f + 1$ redundant copies.

Without loss of generality, henceforth we focus on a tagged traffic flow, and use S and D to denote its source node and destination node, respectively. For each locally generated packet, say P, node S labels P with a unique *sequence number* $SN(P)$, and node D also maintains a *request number* $RN(D)$ to denote the sequence number of the packet that node D is currently requesting for. In other words, all packets with *sequence numbers* less than $RN(D)$ have already been received by node D.

The packet transmission is scheduled as follows: every time node S is selected as the transmitter in an active cell, it conducts the "source-to-destination" transmission if node D is inside the one-hop transmission range; otherwise, it first randomly selects a node from all its one-hop neighbors as the receiver, then conducts the "source-to-relay" transmission or "relay-to-destination" transmission with equal probability [16]. If there is no other node in the one-hop neighborhood, it remains idle for the current time slot.

III. Throughput Capacity and Expected Delivery Delay

A. Some Useful Lemmas

Before deriving the per node throughput capacity and delivery delay in a 2HR-f MANET, we first introduce the following basic lemmas which will be used quite often in the analysis of subsequent sections.

Lemma 1: Consider the source node S of the tagged flow in a general time slot. If we use p_1 to denote the probability that it conducts a source-to-destination transmission and use p_2 to denote the probability that it conducts a source-to-relay or relay-to-destination transmission, then we have

$$p_1 = \frac{1}{\alpha^2}\Big\{\frac{t-\frac{m^2}{n}}{n-1} - \Big(\frac{m^2-1}{m^2}\Big)^{n-1}\frac{(t-1)n+1-m^2}{n(n-1)}\Big\} \quad (2)$$

$$p_2 = \frac{1}{\alpha^2}\Big\{\frac{m^2-t}{n-1}\Big(1-\Big(\frac{m^2-1}{m^2}\Big)^{n-1}\Big) - \Big(\frac{m^2-t}{m^2}\Big)^{n-1}\Big\} \quad (3)$$

where $t = (2\upsilon - 1)^2$.

Lemma 2: Consider the tagged traffic flow in a general time slot, suppose the source node S is delivering copies for some packet P, the destination node D is also requesting for P, i.e., $SN(P) = RN(D)$, and there are in total j $(1 \le j \le f+1)$ copies of P in the network (i.e., node S has already delivered out $j-1$ copies of P to $j-1$ distinct relay nodes). If we denote by $P_r(j)$, $P_d(j)$ and $P_s(j)$ the probability that node D will receive P, the probability that node S will successfully deliver out a copy of P to some new relay (if $j \le f$) and the probability of simultaneous source-to-relay and relay-to-destination transmissions in the next time slot, respectively, then we have

$$P_r(j) = p_1 + \frac{j-1}{2(n-2)}p_2 \quad (4)$$

$$P_d(j) = \frac{n-j-1}{2(n-2)}p_2 \quad (5)$$

$$P_s(j) = \frac{(j-1)(n-j-1)(m^2-\alpha^2)}{4m^2\alpha^4}\sum_{k=0}^{n-5}\binom{n-5}{k}h(k) \cdot\Big\{\sum_{t=0}^{n-4-k}\binom{n-4-k}{t}h(t)\Big(\frac{m^2-2(2\upsilon-1)^2}{m^2}\Big)^{n-4-k-t}\Big\} \quad (6)$$

where

$$h(x) = \frac{(2\upsilon-1)^2\big(\frac{(2\upsilon-1)^2}{m^2}\big)^{x+1} - (4\upsilon^2-4\upsilon)\big(\frac{4\upsilon^2-4\upsilon}{m^2}\big)^{x+1}}{(x+1)(x+2)} \quad (7)$$

The proofs of Lemmas 1 and 2 are omitted here due to space limit, and please kindly refer to [18] for details.

B. Derivations for the Throughput Capacity and Expected Delivery Delay

As shown in [12], the network system under the 2HR-f routing can be characterized by an automatic feedback control system, where the packet dispatching process at source node S and the packet receiving process at destination node D can be defined by two distinct absorbing Markov chains, respectively. If we denote by μ the per node (flow) throughput capacity, i.e., under any input rate less than μ the queue length at each node will never increase to infinity as the time goes to infinity. After applying derivations similar to that in [12], we have the following theorem for the throughput capacity μ.

Theorem 1: Consider a cell partitioned 2HR-f MANET $(1 \le f \le n-2)$, where nodes move according to the i.i.d. mobility model, and each contends for the wireless channel according to the transmission-group based MAC scheme. The per node throughput capacity μ can be given by

$$\mu = \min\left\{\frac{p_1+p_2/2}{1+\sum_{j=1}^{f-1}\prod_{t=1}^{j}\frac{P_d(t)}{p_1+P_d(t+1)}}, P_r(f+1)\right\} \quad (8)$$

The proof of Theorem 1 is omitted here due to space limit and please kindly refer to [12] for details.

Similar to [6], [19]–[21], in this paper we focus on the network *delivery delay* which are caused by nodes' mobility and do not include the part of queuing delay at the source node. We first introduce the following definition about the delivery delay.

Definition 1: For a general packet P at the source node S, the *delivery delay* is defined as the time elapsed between the time slot when node S starts to deliver out copies for the packet P and the time slot when the destination node D receives P given that $SN(P) = RN(D)$.

For a general packet P, if we use A to denote the absorbing state (i.e., the state that node D has received P), the delivery process of packet P under the 2HR-f routing can be defined by a finite state absorbing Markov chain shown in Fig. 2. If we denote by T_d the delivery delay of packet P, then according to the theory of Markov chain [22], T_d can be regarded as the time the Markov chain in Fig. 2 takes to become absorbed given that the chain starts from state 1. Using derivations similar to that in [23], we have the following theorem.

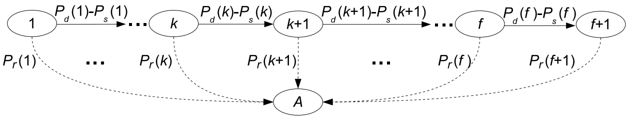


Fig. 2. Finite state absorbing Markov chain for a general packet P, where k $(1 \le k \le f+1)$ denotes a state that there are in total k copies of packet P in the network (including the original one at the source node S). For each transient state, the transition back to itself is not shown for simplicity.

Theorem 2: For a 2HR-f MANET with the transmission-group based MAC scheme, the expected delivery delay $\mathbb{E}\{T_d\}$ can be determined as

$$\mathbb{E}\{T_d\} = \frac{1+\sum_{j=1}^{f-1}\phi(j) + \frac{P_d(f)-P_s(f)}{P_r(f+1)}\phi(f-1)}{p_1+p_2/2} \quad (9)$$

where

$$\phi(j) = \prod_{t=1}^{j}\frac{P_d(t)-P_s(t)}{p_1+p_2/2-P_s(t+1)}$$

The proof of Theorem 2 is omitted here due to space limit, and please kindly refer to [18] for details.

IV. Numerical Results

In this section, we analytically explore how throughput capacity μ varies with delivery delay $\mathbb{E}\{T_d\}$ in terms of the number of users n, the packet redundancy limit f, and the node transmission range υ. A fixed network cell partition with $m = 24$ was adopted in this paper (the other cell partitions can also be easily obtained by our theoretical results). Similar

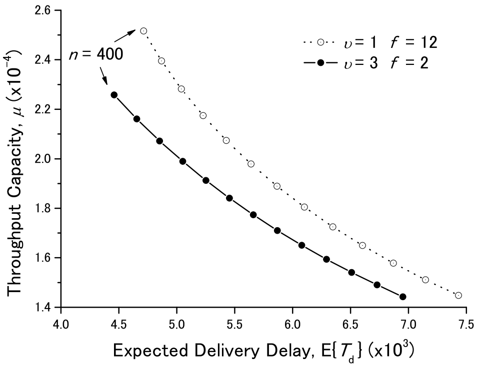


Fig. 3. $(\mathbb{E}\{T_d\}, \mu)$ vs. n for the cases of $(\upsilon = 1, f = 12)$ and $(\upsilon = 3, f = 2)$ with $400 \leq n \leq 1000$.

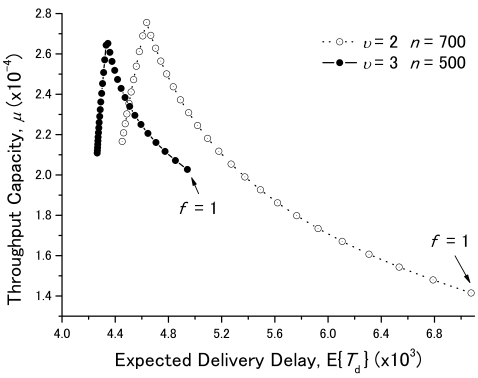
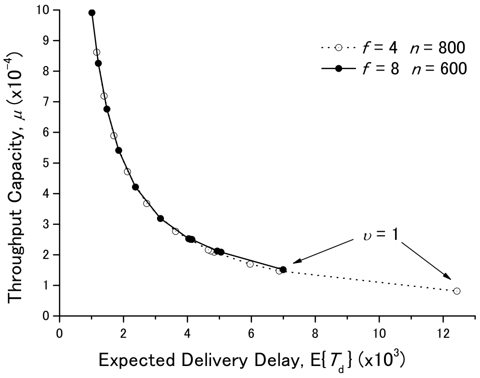
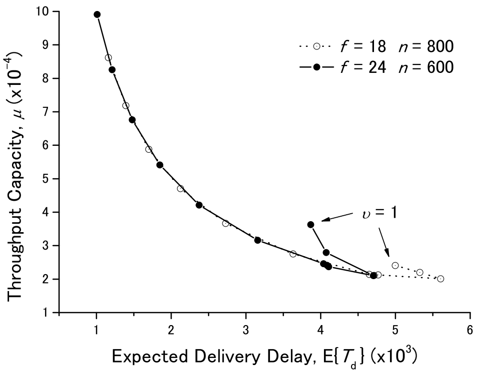


Fig. 4. $(\mathbb{E}\{T_d\}, \mu)$ vs. f for the cases of $(\upsilon = 2, n = 700)$ and $(\upsilon = 3, n = 500)$ with $1 \leq f \leq 32$.



(a) $(\mathbb{E}\{T_d\}, \mu)$ vs. υ for the cases of $(f = 4, n = 800)$ and $(f = 8, n = 600)$ with $1 \leq \upsilon \leq 12$.



(b) $(\mathbb{E}\{T_d\}, \mu)$ vs. υ for the cases of $(f = 18, n = 800)$ and $(f = 24, n = 600)$ with $1 \leq \upsilon \leq 12$.

Fig. 5. Illustration of the relationship between $(\mathbb{E}\{T_d\}, \mu)$ and the node transmission range υ.

to the settings adopted in [24], [25], the guard factor Δ here was fixed as $\Delta = 1$.

A. Under Fixed υ and f

We first examine how the throughput capacity μ varies with the delivery delay $\mathbb{E}\{T_d\}$ in terms of the number of users n. Two cases of $(\upsilon = 1, f = 12)$ and $(\upsilon = 3, f = 2)$ with $400 \leq n \leq 1000$ are presented and the corresponding results are summarized in Fig. 3. We can see that for both the two cases there, as n varies from 400 to 1000, μ decreases almost linearly with $\mathbb{E}\{T_d\}$. It is also noticed that μ (resp. $\mathbb{E}\{T_d\}$) monotonically decreases (resp. increases) with n. This can be interpreted as follows, for a fixed network region, as n and thus the node density n/m^2 gradually increases up, the network becomes crowded which leads to severe contention and decrease of the network performances.

B. Under Fixed υ and n

Fig. 4 shows the relationship between the throughput capacity μ and delivery delay $\mathbb{E}\{T_d\}$ under fixed settings of υ and n. It's interesting to notice that the behaviors of μ with $\mathbb{E}\{T_d\}$ are divided into two parts: as $\mathbb{E}\{T_d\}$ monotonically decreases (with f increasing from 1 to 32), μ first gradually increases until some point, then diminishes quickly. The monotonically decreasing behavior of $\mathbb{E}\{T_d\}$ can be attributed to the following reason that as f increases up, more relay nodes will help carrying copies for a packet and thus shorten the packet delivery delay. However, deliberate researches are required to explain the throughput behavior in the second part where both $\mathbb{E}\{T_d\}$ and μ are decreasing.

A further careful observation of Fig. 4 indicates that beyond some threshold value ($f = 22$ in the case $(\upsilon = 2, n = 700)$ and $f = 15$ in the case $(\upsilon = 3, n = 500)$), μ is extremely sensitive to the variations of $\mathbb{E}\{T_d\}$, and there exists some limiting point of $(\mathbb{E}\{T_d\}, \mu)$ with f. The limiting behavior can be explained as follows: for a fixed network setting of n and υ, the network performance can not be improved any more if the maximum number of relay nodes, i.e., f, increases beyond some value.

C. Under Fixed f and n

We proceed to evaluate the relationship between throughput capacity μ and delivery delay $\mathbb{E}\{T_d\}$ under fixed f and n. With

$m = 24$, υ can be determined as $1 \leq \upsilon \leq 12$. We consider two network scenarios $n = 800, 600$ with two settings of f for each scenario, i.e., $(f = 4, n = 800)$, $(f = 8, n = 600)$, $(f = 18, n = 800)$ and $(f = 24, n = 600)$, and summarize the corresponding results in Figs. 5a and 5b, respectively.

Fig. 5a shows clearly that under both the two settings of f and n there, as υ varies from 1 to 12, the curve of case $(f = 4, n = 800)$ almost coincides with that of case $(f = 8, n = 600)$, and the relationships between μ and $\mathbb{E}\{T_d\}$ there can be well approximated with the curve $\mu \cdot \mathbb{E}\{T_d\} = 1$. Such nice matchings with the curve $\mu \cdot \mathbb{E}\{T_d\} = 1$ can also be observed from Fig. 5b as υ increases beyond some value ($\upsilon = 3$ for both cases there). It could be attributed to the following reason that, as υ increases up, the MANET is becoming one-hop network where the node transmission range can cover the whole network region and thus $\mu = 1/\mathbb{E}\{T_d\}$. Our results indicate that such property may also hold in 2HR-f MANETs even with relatively small transmission range (i.e., υ).

A further careful comparison between Figs. 5a and 5b indicates that the impacts of node transmission range υ on μ and $\mathbb{E}\{T_d\}$ are two folds. One is advantageous, i.e., a bigger transmission range could lead to a higher probability to meet the destination node or some relay node and thus a faster message delivery speed. The other is disadvantageous, i.e., a bigger transmission range would result in a wide interference range (i.e., a bigger α) which limits the spatial reuse of whole network, and thus reduces the number of simultaneous transmissions. The performance trade-off between these two folds may be negligible if f is relatively small compared with the network size n (as shown in Fig. 5a); otherwise, $(\mathbb{E}\{T_d\}, \mu)$ may have different varying tendencies as υ increases. For example, for the case of $(f = 24, n = 600)$ in Fig. 5b, μ (resp. $\mathbb{E}\{T_d\}$) first decreases (resp. increases) until $\upsilon = 3$, then increases (resp. decreases) as $\upsilon \geq 3$.

V. Conclusion

In this paper we have investigated the relationship between throughput capacity μ and delivery delay $\mathbb{E}\{T_d\}$ in MANETs. In particular, we derived closed-form expressions for μ and $\mathbb{E}\{T_d\}$ in a 2HR-f MANET with generalized node transmission range. Extensive numerical results were provided to show how μ varies with $\mathbb{E}\{T_d\}$ in terms of the number of users n, the packet redundancy limit f and the node transmission range υ. Our results indicate that under fixed υ and f, μ varies almost linearly with $\mathbb{E}\{T_d\}$; while under fixed υ and n, as $\mathbb{E}\{T_d\}$ decreases, μ first increases until some value and then decreases. It's interesting to find that under fixed f and n, the relationship between μ and $\mathbb{E}\{T_d\}$ can be well approximated with $\mu \cdot \mathbb{E}\{T_d\} = 1$, similar to that in one-hop networks.

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