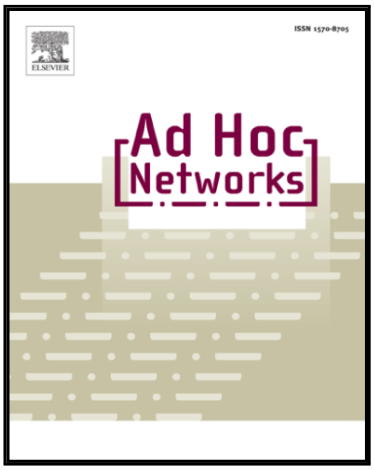

On the Packet Delivery Delay Study for Three-Dimensional Mobile Ad Hoc Networks

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On the Packet Delivery Delay Study for Three-Dimensional Mobile Ad Hoc Networks

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***Abstract*—This paper studies the packet delivery delay performance in three-dimensional mobile ad hoc networks (3D MANETs). Available work mainly focuses on the performance study in two-dimensional MANETs (2D MANETs), which cannot support delay-intensive applications in 3D MANETs. To explore the packet delivery delay performance in 3D MANETs, this paper adopts two-hop relay algorithm with packet replication for packet routing. With such an algorithm, source node can transmit a packet to at most f distinct relay nodes, which then help to forward the packet to its destination node. The algorithm is flexible such that the packet delivery process can be controlled through a proper setting of f. Specially, a general Markov chain theoretical framework is developed to model the packet delivery process under the algorithm in 3D MANETs. Based on the theoretical framework, the closed-form expressions are further derived for mean and relative standard deviation of packet delivery delay. Finally, extensive simulation and numerical results are provided to validate our theoretical models and illustrate the impact of network parameters on packet delivery delay performance in 3D MANETs.**

***Index Terms*—3D MANETs, delay performance, Markov chain framework.**

I. Introduction

Three-dimensional mobile ad hoc networks (3D MANETs) are a class of flexible and distributed peer-to-peer networks, where mobile nodes move within 3D space and can communicate with each other via wireless link without any pre-existing infrastructure. As 3D MANETs can be rapidly deployed and flexibly reconfigured, they are appealing many critical applications: various military units communication (i.e., aircrafts, troops, and fleets) for modern combat, underwater vehicles communication for ocean surveillance, and unmanned aerial vehicles communication for disaster monitoring. To support these applications with different delay requirements in 3D MANETs, understanding the packet delivery delay performance in such networks is of fundamental importance.

The packet delivery delay performance for 2D MANETs has been extensively studied in the literature, in terms of its order sense scaling laws with network size or its closed-form analytical models (see Section II for related work). However, all the above work is conducted on 2D MANETs only. Recently, some initial work has focused on the study of performance for 3D MANETs, such as throughput capacity [1] and delivery rate [2], which are defined as the maximum packet input rate that the network can stably support and the probability that a packet is successfully transmitted to its destination, respectively.

It is notable that the packet delivery delay performance in 3D MANETs has not been investigated, which significantly hinders their applications. Different from the aforementioned work, this paper studies the packet delivery delay performance in 3D MANETs. This paper made a significant improvement on our previous work of [3]. In [3], we only studied the packet delivery delay. In this paper, we study the packet delivery delay as well as corresponding relative standard deviation. We also add new simulation results to validate the theoretical models on the packet delivery delay and corresponding relative standard deviation under the random walk and random waypoint mobility models, besides independent and identically distributed (i.i.d.) mobility model [4]. More simulated and numerical results with different parameters are further provided to do performance analysis and show the packet delivery performance in 3D MANET is different with that in 2D MANET. The main contributions of this paper are summarized as follows.

- First, a Markov chain theoretical framework is developed to model the packet delivery process under the two-hop relay algorithm with packet replication.
- Then, based on the developed theoretical framework, closed-form expressions are further derived for mean and relative standard deviation of packet delivery delay.
- Finally, simulation and numerical results are provided to validate our theoretical models and illustrate our findings.

The remainder of this paper is organized as follows. We review related work in Section II. We introduce system models in Section III. Section IV presents two-hop relay algorithm with packet replication and corresponding transmission scheduling. In Section V, we first develop a Markov chain theoretical framework and derive some related basic probabilities. Section VI derives closed-form expressions for mean and relative standard deviation of packet delivery delay. Simulation and numerical results are presented in Section VII. Finally, Section VIII concludes this paper.

II. Related Work

There have been many research efforts in the literature to study the packet delivery delay performance in MANETs. The

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packet delivery delay performance in two-hop relay MANETs is studied in [5]–[7], where [5] considers random walk mobility model, [6] considers restricted mobility model, and [7] considers Brownian mobility model. Later, the packet delivery delay performance is explored in two-hop relay MANETs under discrete random direction model and hybrid random walk model [8], where the network area is evenly divided into multiple equal-sized cells.

It is notable that the above work focuses on the study of order sense scaling laws on packet delivery delay in MANETs. Although the order sense results are helpful for us to understand the growth rate of packet delivery delay with network size, they tell us little about the exact packet delivery delay. In practice, however, such exact packet delivery delay is of great interest for network designers. Some work is now available on the exact packet delivery delay study in MANETs. By establishing an ordinary differential equation, a close-form expression is derived for the packet delivery delay in MANETs [9]. Based on an ordinary differential equation, the exact packet delivery delay and its variants are further studied under epidemic routing in [10]. Later, the exact packet delivery delay is examined in two-hop relay MANETs [11].

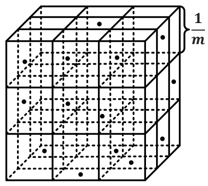


Fig. 1. Network model

III. SYSTEM MODELS

A. Network Model

We consider a time-slotted network with n mobile nodes uniformly distributed in a unit cube area. The cube area is evenly divided into $m \times m \times m$ equal-sized cells, as shown in Fig. 1. The mobile nodes roam from one cell to another following independent and identically distributed (i.i.d.) mobility model [4]. Under i.i.d. mobility model, at the beginning of each time slot, each node independently selects one from all m^3 cells with the equal probability to move into, and stays at the selected cell for the rest of the time slot.

B. Communication Model

To avoid interferences from other transmitters in the same time slot, we adopt the widely used Protocol Model [12] here. Suppose that all the nodes employ the same fixed transmission range r, at some time slot t a node T_x is transmitting to another node R_x. We use $d_{T_xR_x}(t)$ to denote Euclidean distance between T_x and R_x. To guarantee the transmission from T_x to R_x to be successful at the time slot, the following two conditions should hold according to the Protocol Model:

1) $d_{T_xR_x}(t) \leq r$,
2) $d_{T_kR_x}(t) \geq (1+\Delta)r$ for every other node T_k transmitting simultaneously at the same time slot t,

where guard-factor Δ is a positive number for interference prevention. We assume that the total number of bits transmitted per time slot is fixed and normalized to one packet.

C. Traffic Model

Similar to [4], [13]–[17], we adopt the permutation traffic pattern in our study. Under this traffic model, there are in total n distinct source-destination pairs in the considered MANET, i.e. $1 \rightarrow 2, 2 \rightarrow 3, ..., (n-1) \rightarrow n, n \rightarrow 1$. Here for $T_x = 1, ..., n-1$, node T_x generates traffic destined for node $T_x + 1$ and node n generates traffic destined for node 1. Therefore, each node is a source of its locally generated traffic flow and also a destination of a traffic flow originated from some other node. Each node can serve as a potential relay that helps to forward packet for other $n-2$ traffic flows.

IV. TWO-HOP RELAY ALGORITHM WITH PACKET REPLICATION AND TRANSMISSION SCHEDULING

A. Two-hop Relay Algorithm with Packet Replication

We adopt two-hop relay algorithm for packet routing in 3D MANETs [13], as shown in Fig. 2. Under this algorithm, packet delivery process can be summarized as two phases. In phase 1, a packet is transmitted to an intermediate node (relay node) from its source node, and then in phase 2, the packet is transmitted to its destination node from the relay node. It is notable that the source node can directly transmit a packet to its destination node once such a transmission opportunity arises, and thus every packet goes through at most two hops to reach its destination node. For increasing packet transmission opportunity, each packet at source node can be replicated to at most f distinct relay nodes in this paper.

Without loss of generality, we focus on a tagged traffic flow and denote its source node and destination node as S and D, respectively. Since each node can be a potential relay for other $n-2$ traffic flows (except the two traffic flows originated from and destined for itself), thus to support the operation of the algorithm, each node is equipped with n individual queues at its buffer: one send-queue for storing the packets that are locally generated at the node and waiting for their copies to be distributed, one already-sent queue for storing packets whose f copies have already been distributed out but their reception

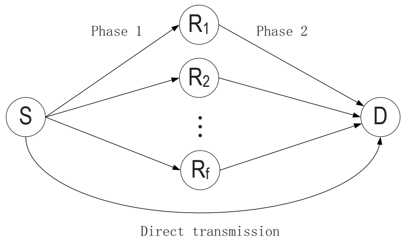


Fig. 2. Illustration of two-hop relay algorithm.

statuses are not confirmed yet (from destination node), and $n-2$ parallel relay-queues for storing packets of other traffic flows (one queue per traffic flow).

When S gets a transmission opportunity at some time slot, it will conduct the following operations:

1) If D is within the transmission range of S, then S conducts a Source-to-Destination transmission. Under such transmission, S directly transmits the packet to D from its send-queue or its already-sent queue.

2) Otherwise, S randomly selects a node (said node V) from its transmission range, and then does one of the following two transmissions with equal probability.

- Source-to-Relay transmission: If V is not carrying any copy of the packet which S is transmitting, S transmits a copy of the packet to V. Otherwise, S keeps idle.
- Relay-to-Destination transmission: If S carries a copy of the packet in its relay-queue and V is requesting for the packet, then S, serving as a relay, transmits the copy to V. Otherwise, S keeps idle.

It is notable that under Source-to-Relay transmission, if S has already transmitted out all f copies of the packet, then it removes the packet from its send-queue and inserts the packet into its already-sent queue.

B. Transmission Scheduling

To support as many simultaneous transmissions as possible without interfering with each other in MANETs, we adopt a transmission-set based scheduling scheme [18], [19]. Under this scheduling scheme with parameter α, a transmission-set is a subset of cells where any two cells have a distance of some multiples of α cells in three directions along the x, y and z axes, respectively, and all the cells there could transmit simultaneously without interfering with each other. According to the definition of transmission-set, all m^3 cells are actually divided into α^3 distinct transmission-sets. Fig. 3 shows an example of $m = 12$ and $\alpha = 4$, where there are 64 transmission-sets in total and all shaded cells belong to the same transmission-set. We assume that each transmission-set (and thus each cell in the transmission-set) can get transmission opportunity in turn in every α^3 time slots, and call a cell an active cell if it gets transmission opportunity. In a time slot, if more than one nodes are residing in an active cell, only one node is randomly selected as the transmitter (transmitting node).

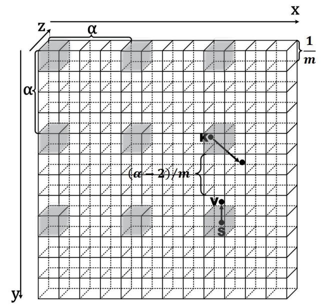


Fig. 3. Illustration of a transmission-set with $m = 12$ and $\alpha = 4$, where all the shaded cells in the directions of x and y axes belong to the same transmission-set. In the same transmission-set, the shaded cells in the direction of z axis is not shown for simplicity.

To guarantee that these transmitting nodes in all the cells of a transmission-set can transmit simultaneously without interfering with each other, we need to properly determine the parameter α. We consider a transmission scenario [13], where a node in an active cell can transmit to another node in the same cell or in its 26 adjacent cells. Here two cells are called adjacent cells if they share a common point. Thus, the maximum transmission distance denoted as r from a node to another node is calculated as $2\sqrt{3}/m$, as shown in Fig. 4. Due to the wireless interference, only these nodes that are sufficiently far away could simultaneously transmit without interfering with each other. As shown in Fig. 3, suppose that a node S in an active cell is transmitting to another node V. With the transmission scenario in [13], any other transmitting node K in the same transmission-set is at least $(\alpha-2)/m$ away from V. According to the Protocol Model [12], we have

$$(\alpha-2)/m \geq (1+\Delta)\cdot r. \tag{1}$$

Substituting $r = 2\sqrt{3}/m$ into (1) yields

$$\alpha \geq (1+\Delta)2\sqrt{3}+2. \tag{2}$$

Since α is an integer and $\alpha \leq m$, we have

$$\alpha = \min\left\{\left\lceil(1+\Delta)2\sqrt{3}\right\rceil+2, m\right\} \tag{3}$$

where $\lceil x \rceil$ is ceiling function, returning the smallest integer no smaller than x.

V. Markov Chain Theoretical Framework

In this section, we develop a Markov chain theoretical framework to depict the packet delivery process under two-

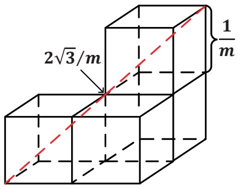


Fig. 4. The maximum transmission distance between a transmitting node and its receiving node

hop relay algorithm with packet replication, and derive some related basic probability results.

A. Markov Chain Theoretical Framework

For a tagged traffic flow with source node S and destination node D and a given packet, we use i $(1 \leq i \leq f+1)$ to denote a general transient state under which there are in total i copies of the packet in the network (including one original packet at the source node). According to the operations of the algorithm, for a transient state i at current time slot, only one of the following five transmission scenarios may happen in the next time slot:

- SD Scenario: Source-to-Destination transmission, i.e., S will successfully transmit the packet to D.
- SR Scenario: Source-to-Relay transmission only, i.e., S will successfully transmit the packet to a relay node while none of relay nodes transmits the packet to D.
- RD Scenario: Relay-to-Destination transmission only, i.e., A relay node will successfully transmit the packet to D while S fails to transmit the i-th copy to relay node.
- $SR+RD$ Scenario: both simultaneous Source-to-Relay and Relay-to-Destination transmissions, i.e., these two transmissions will happen simultaneously.
- Selfloop Scenario: a state will transit to itself.

If we use A to denote an absorbing state indicating that D has received the packet at this state, then the packet delivery process under the algorithm can be modeled as a finite state absorbing Markov chain as shown in Fig. 5.

Remark 1: As shown in Fig. 5, for the tagged traffic flow and a given packet, suppose that the current state i will transit to itself in the next time slot, it means that the corresponding transmitting node does not transmit the packet to another node. Here the current state i represents that there are in total i copies of the packet in the network (including the original one at the source node). For example, if the current state is 1, then the transmitting node (i.e.,the source node) does not transmit the packet to a relay node or its destination node in the next time slot.

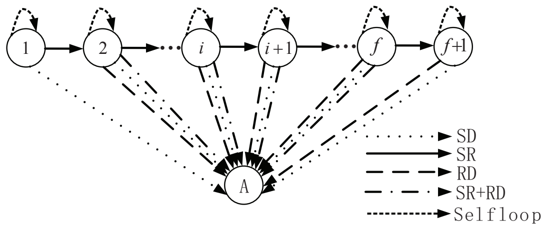


Fig. 5. Absorbing Markov chain theoretical framework.

In Fig. 5, for the case of the state 1, it represents that there is only one packet in the network, i.e., the original packet at the source node, thus one of these three transitions of SD Scenario, SR Scenario and Selfloop Scenario may happen in the next time slot.

For the case of the state f+1, it represents that there are f+1 copies of the packet in the network, where the source node has already transmitted out all f copies to distinct relay nodes such that it will not perform Source-to-Relay transmission, thus one of these three transitions of SD Scenario, RD Scenario and Selfloop Scenario may happen in the next time slot.

For the case of each state between states 2 and f, it represents that the source node has not transmitted out all f copies of the packet and some relay nodes are carrying the copies, thus one of these five transitions of SD Scenario, SR Scenario, RD Scenario, $SR+RD$ Scenario, and Selfloop Scenario may happen in the next time slot.

B. Some Basic Probability Results

For an analytical study of packet delivery delay performance, we need to derive some basic probabilities related to the developed Markov chain theoretical framework. Here we give the following two lemmas.

Lemma 1: For a given time slot and a tagged traffic flow, we use p_{sd}, p_{srd} to denote the probability that the source node S conducts a Source-to-Destination transmission and the probability that S conducts a Source-to-Relay or Relay-to-Destination transmission, respectively. Then we have

$$p_{sd}=\frac{1}{\alpha^3}\Big\{\frac{27-m^3}{n-1}+\frac{m^3}{n}-\frac{26}{n-1}\Big(\frac{m^3-1}{m^3}\Big)^{n-1} +\Big(\frac{m^3}{n-1}-\frac{m^3}{n}\Big)\Big(\frac{m^3-1}{m^3}\Big)^{n}\Big\} \quad (4)$$

$$p_{srd}=\frac{m^3-27}{m^3\alpha^3}\Big\{\sum_{k=1}^{n-2}\binom{n-2}{k}\Big(\frac{1}{m^3}\Big)^k\Big(\frac{m^3-1}{m^3}\Big)^{n-2-k}\frac{1}{k+1} +\sum_{k=1}^{n-2}\binom{n-2}{k}\Big(\frac{26}{m^3}\Big)^k\Big(\frac{m^3-27}{m^3}\Big)^{n-2-k}\Big\} \quad (5)$$

Lemma 2: For a given time slot and a tagged traffic flow, suppose that there are in total g copies of the packet in the network(including an original packet at the source node). We use $P_r(g)$, $P_d(g)$ and $P_{sim}(g)$ to denote the probability that D will receive the packet, the probability that S will successfully transmit a copy of the packet to a relay node no carrying the packet and the probability that both Source-to-Relay and Relay-to-Destination transmissions happen simultaneously, respectively, in the next time slot. Then we have

$$P_r(g) = p_{sd} + \frac{g-1}{2(n-2)}\cdot p_{srd} \quad (6)$$

$$P_d(g) = \frac{n-g-1}{2(n-2)}\cdot p_{srd} \quad (7)$$

$$P_{sim}(g) = \frac{(g-1)(n-g-1)(m^3-\alpha^3)}{4m^3\alpha^6}\sum_{k=0}^{n-5}\binom{n-5}{k}h(k) \cdot\Big\{\sum_{t=0}^{n-4-k}\binom{n-4-k}{t}h(t)\Big(1-\frac{54}{m^3}\Big)^{n-4-k-t}\Big\} \quad (8)$$

where

$$h(x) = \frac{27(\frac{27}{m^3})^{x+1}-26(\frac{26}{m^3})^{x+1}}{(x+1)(x+2)} \quad (9)$$

The proofs of above lemmas can be found in the Appendix.

VI. Packet Delivery Delay Modeling

With the help of the Markov chain theoretical framework and related basic probability results in V, this section gives the derivation process of the closed-form expressions for expected value and relative standard deviation of packet delivery delay under the two-hop relay algorithm with packet replication. We first introduce the following definition of packet delivery delay.

Definition 1: For a tagged flow and a given packet, the delivery delay of a packet in considered 3D MANET is defined as time duration between the time slot that source node S starts to transmit the packet and the time slot that destination node D receives the packet.

A. Expected Packet Delivery Delay

We use a_i to denote the time that the Markov chain takes to reach absorbing state A starting from the state i, where $1 \le i \le f+1$. We use q_{ij} to denote the probability that the state i transits to the state j, and then according to the theory of Markov chain [20], the expected value $E\{a_i\}$ of a_i is given by

$$E\{a_i\} = \frac{1+\sum_{j\in[1,f+1],j\neq i} q_{ij}\cdot E\{a_j\}}{1-q_{ii}}. \quad (10)$$

Thus the expected value $E\{a_1\}$ of a_1 that just corresponds to the expected packet delivery delay, can be determined as

$$E\{a_1\} = \frac{1+\sum_{j\in[1,f+1],j\neq 1} q_{1j}\cdot E\{a_j\}}{1-q_{11}} \quad (11)$$

$$= \frac{1+P_d(1)\cdot E\{a_2\}}{P_d(1)+P_r(1)} \quad (12)$$

$$= \frac{1}{P_d(1)+P_r(1)} + \frac{P_d(1)}{P_d(1)+P_r(1)}\Big\{\frac{1}{P_d(2)+P_r(2)} +\frac{P_d(2)}{P_d(2)+P_r(2)}E\{a_3\}\Big\} \quad (13)$$

$$= \frac{1}{P_d(1)+P_r(1)} + \frac{P_d(1)}{P_d(1)+P_r(1)}\frac{1}{P_d(2)+P_r(2)} +\frac{P_d(1)}{P_d(1)+P_r(1)}\frac{P_d(2)}{P_d(2)+P_r(2)}E\{a_3\} \quad (14)$$

We can see from Fig.5 that if $j > 2$, $q_{1j} = 0$, and if $j = 2$, $q_{1j} = P_d(1)$ because both q_{1j} and $P_d(1)$ denote the probability that SR Scenario happens, i.e., the source node can successfully transmit a copy of the packet to a relay node. We have

$$\sum_{j\in[1,f+1],j\neq 1} q_{1j}\cdot E\{a_j\} = P_d(1)\cdot E\{a_2\}. \quad (15)$$

Under the state 1, the Relay-to-Destination transmission will not happen in the next time slot, thus $P_r(1)$ denotes the probability that SD Scenario happens, i.e., the source node can successfully transmit the packet to its destination node. Since the q_{11} denotes the probability that the state 1 transits to itself, we have

$$1-q_{11} = P_d(1)+P_r(1). \quad (16)$$

Substituting (15) and (16) into (11), then (12) follows.

Based on (10), we continue to iterate the formula(14), and then $E\{a_1\}$ is determined as

$$E\{a_1\}=\frac{1}{P_d(1)+P_r(1)} + \sum_{j=1}^{f-1}\Big\{\Big(\Pi_{k=1}^{j}\frac{P_d(k)}{P_d(k)+P_r(k)}\Big) \cdot\frac{1}{P_d(j+1)+P_r(j+1)}\Big\} + \Big(\Pi_{k=1}^{f}\frac{P_d(k)}{P_d(k)+P_r(k)}\Big) \cdot E\{a_{f+1}\} \quad (17)$$

where

$$E\{a_{f+1}\} = \frac{1}{P_r(f+1)} \quad (18)$$

B. Relative Standard Deviation

We use RSD and Var$\{a_1\}$ to denote the relative standard deviation and variance of packet delivery delay, respectively. The RSD is defined as

$$RSD = \frac{\sqrt{Var\{a_1\}}}{E\{a_1\}}. \tag{19}$$

Since Var$\{a_1\}$ can be determined as Var$\{a_1\} = E\{{a_1}^2\} - \big(E\{a_1\}\big)^2$, and $E\{a_1\}$ can be determined by (17), we only need to derive the $E\{{a_1}^2\}$ here.

According to the definition of a_i, we can see that $E\{{a_i}^2\}$ is given by

$$\begin{aligned} E\{{a_i}^2\} &= \sum_{j=1}^{f+1} q_{ij} E\big\{(1+a_j)^2\big\} \\ &= 1 + 2\sum_{j=1}^{f+1} q_{ij} E\{a_j\} + \sum_{j=1}^{f+1} q_{ij} \cdot E\{{a_j}^2\} \end{aligned} \tag{20}$$

Let $\mathbf{a}^{(j)} = \big(E\{{a_1}^j,\}, E\{{a_2}^j,\}, \ldots E\{{a_{f+1}}^j,\}\big)^T$, then we can rearrange (20) as

$$\mathbf{I} \cdot \mathbf{a}^{(2)} = \mathbf{c} + 2\mathbf{Q} \cdot \mathbf{a}^{(1)} + \mathbf{Q} \cdot \mathbf{a}^{(2)} \tag{21}$$

where $\mathbf{c}$ is the $(f+1) \times 1$ column vector with all entries being 1, i.e., $\mathbf{c} = \{1, 1, \ldots, 1\}^T$. Then, according to [20], we have

$$\mathbf{a}^{(1)} = (\mathbf{I} - \mathbf{Q})^{-1} \cdot \mathbf{c} \tag{22}$$

$$\mathbf{a}^{(2)} = (\mathbf{I} - \mathbf{Q})^{-1} \Big\{\mathbf{I} + \mathbf{2Q} \cdot (\mathbf{I} - \mathbf{Q})^{-1}\Big\} \mathbf{c} \tag{23}$$

Since $E\{\mathbf{a_1}^2\} = \mathbf{e} \cdot \mathbf{a}^{(2)}$, where $\mathbf{e} = \{1, 0, \ldots, 0\}$, the $E\{{a_1}^2\}$ can be derived based on $\mathbf{Q}$.

Since the transitions in the Markov chain of Fig.5 happen only among the transient states of the same row or neighboring rows, the matrix $\mathbf{Q}$ there can be defined as

$$\mathbf{Q} = \begin{bmatrix} q_{1,1} & q_{1,2} & & & & & \\ & q_{2,2} & q_{2,3} & & & & \\ & & \ddots & \ddots & & & \\ & & & q_{i,i} & q_{i,i+1} & & \\ & & & & \ddots & \ddots & \\ & & & & & q_{f,f} & q_{f,f+1} \\ & & & & & & q_{f+1,f+1} \end{bmatrix}$$

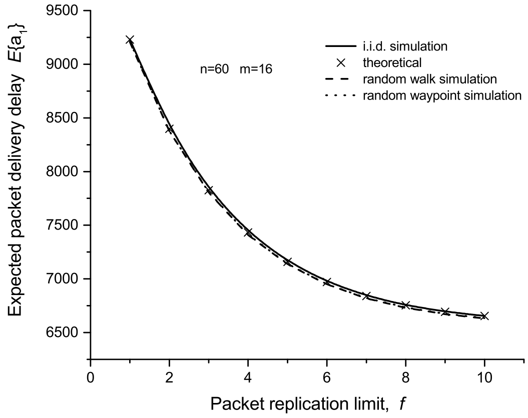
The size of matrix $\mathbf{Q}$ is $(f+1) \times (f+1)$, the nonzero entries of matrix $\mathbf{Q}$ can be determined as

$$q_{i,i} = \begin{cases} 1 - p_{sd} - \frac{p_{srd}}{2} + P_{sim}(i), & \text{if} \quad 1 \le i \le f, \\ 1 - P_r(f+1), & \text{if} \quad i = f+1. \end{cases} \tag{24}$$

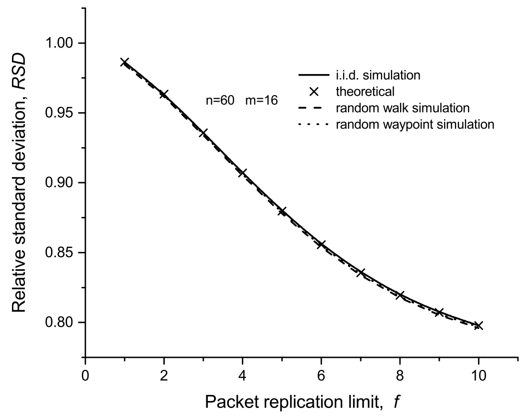
$$q_{i,i+1} = P_d(i) - P_{sim}(i), \quad \text{if} \quad 1 \le i \le f. \tag{25}$$

VII. Numerical Results

In this section, we first provide simulation results to validate our theoretical models, and then illustrate the impact of network parameters on the packet delivery delay performance.



(a) $E\{a_1\}$ versus f



(b) RSD versus f

Fig. 6. Comparison between simulation results and theoretical ones for model validation.

A. Simulation Settings

We developed a simulator using C++ language to simulate the packet delivery process under the two-hop relay algorithm with packet replication in 3D MANETs (now publicly available at [21]). The guard factor Δ in Protocol Model is fixed as $\Delta = 1$, and thus the transmission-set is defined with $\alpha = \min\{9, m\}$. Besides the simulation under i.i.d. mobility model considered in this paper, we also implemented the simulator for the popular random walk model and random waypoint model, which are defined as follows.

- Random Walk Model [16]: At the beginning of each time slot, each node either stays inside its current cell or moves to one of its 26 adjacent cells, with the same probability $1/27$.
- Random Waypoint Model [22]: At the beginning of each time slot, each node independently and randomly generates a three-dimensional vector $d = [d_x, d_y, d_z]$, where the values of d_x, d_y and d_z are uniformly drawn from $[1/m, 3/m]$. The node then moves a distance of d_x,

d_y and d_z along the x-axis, y-axis and z-axis, respectively.

We focus on a tagged traffic flow with source node S and destination node D, and a given packet. The basic idea of the simulation for the packet delivery delay performance using C++ is included in the following Algorithm 1. In Algorithm 1, we use Sim to denote the number of independent simulations, use $Total\_time$ to denote the sum of packet delivery delay in all Sim simulations, use $Time\_slot$ to denote the packet delivery delay in each simulation, use $delivery\_delay[t]$ to denote the packet delivery delay in the t_{th} simulation, and use $flag$ to denote whether or not D receives the given packet, where if D receives the given packet, and then $flag = 1$; otherwise, $flag = 0$.

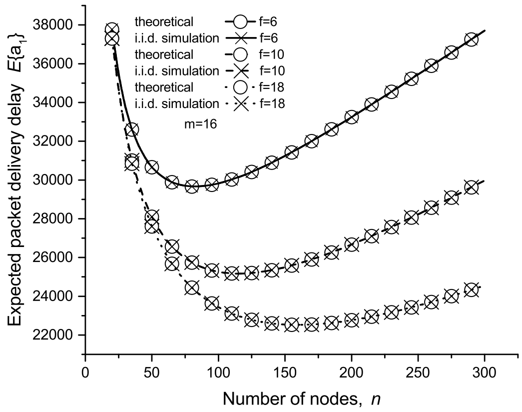
Algorithm 1 Simulated packet delivery delay performance:

1. **Input:** n nodes are randomly generated in the considered network; The number of independent simulations,$Sim = 10^6$;
2. **Output:** The packet delivery delay performance, $(E\{a_1\}, RSD)$;
3. $Total\_time = 0$;
4. **for** $t = 1$; $t <= Sim$; $t++$ **do**
5. $\quad Time\_slot = 0$, $flag = 0$;
6. $\quad$ **while** $(flag\ != 1)$ **do**
7. $\quad\quad Time\_slot++$;
8. $\quad\quad$ Each node updates its position according to node mobility model;
9. $\quad\quad$ Under the transmission-set based scheduling scheme, each node may be scheduled to perform a data transmission, where if D receives the given packet, and then $flag = 1$;
10. $\quad$ **end while**
11. $\quad delivery\_delay[t] = Time\_slot$;
12. $\quad Total\_time += Time\_slot$;
13. **end for**
14. The simulated standard deviation $Var\{a_1\}$ is the sample standard deviation, thus $Var\{a_1\} = \sqrt{\frac{1}{Sim-1}\sum_{t=1}^{Sim}(delivery\_delay[t] - E\{a_1\})}$;
15. $E\{a_1\} = Total\_time/Sim$;
16. $RSD = \frac{\sqrt{Var\{a_1\}}}{E\{a_1\}}$;

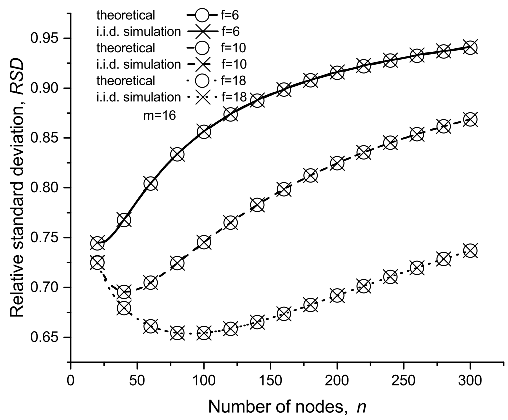
Remark 2: Similar to previous studies [15], [23], [24], we consider that all the nodes in the network share a common half-duplex channel for data transmission and the total number of bits transmitted per time slot is fixed and normalized to one packet. It is notable that the network structure to switch from 2D to 3D becomes more complex. This is because in 3D MANET it involves not only highly dynamic topology, but also issues related to medium contention, node connectivity, data transmission, which leads to more complex theoretical analysis on the packet delivery delay performance.

B. Model Validation

Extensive simulations were conducted to validate our theoretical models. Given that the network scenario $\{m = 16, n = 60\}$ and packet replication limit f varies from 1 to 10, the theoretical and simulated results are summarized in Fig. 6. Fig. 6 indicates that the simulation results under i.i.d. mobility model match nicely with the theoretical ones. Therefore, our theoretical model can accurately predict the packet delivery delay performance under the two-hop relay algorithm in 3D MANETs.



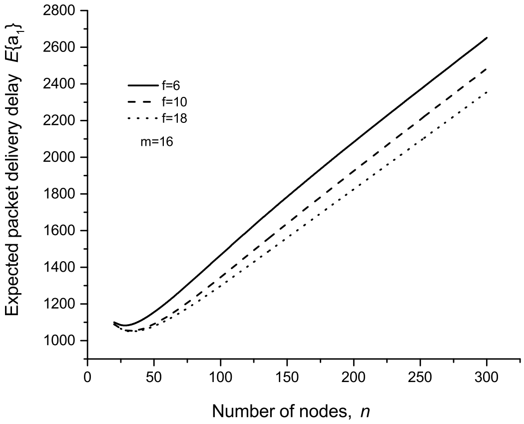
(a) $E\{a_1\}$ versus n



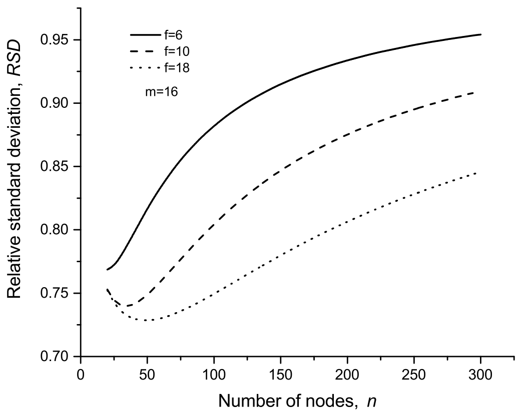
(b) RSD versus n

Fig. 7. The impact of number of nodes n on packet delivery delay performance in 3D MAENT

Another interesting observation from Fig. 6 that for the network scenario, the simulated packet delivery delay performance under the random walk and random waypoint models almost agree with those under the i.i.d. mobility model. According to the definitions of i.i.d., random walk and random waypoint mobility models, these three mobility models are different with each other. However, as shown in [15], [25], for a cell-partitioned network, the average delay under the i.i.d. mobility model is also identical to that under other non-i.i.d. mobility models only if they have the same steady-state distribution of nodes locations, like the random walk mobility model and random waypoint mobility model. Therefore, our

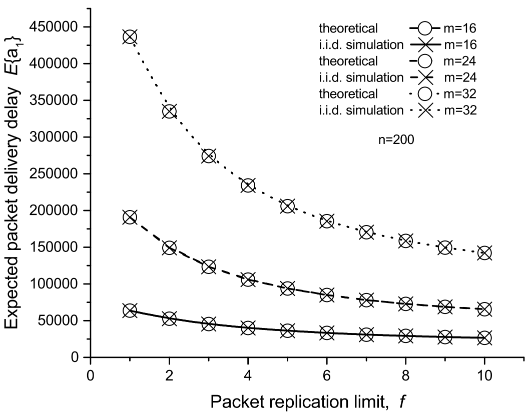


(a) $E\{a_1\}$ versus n

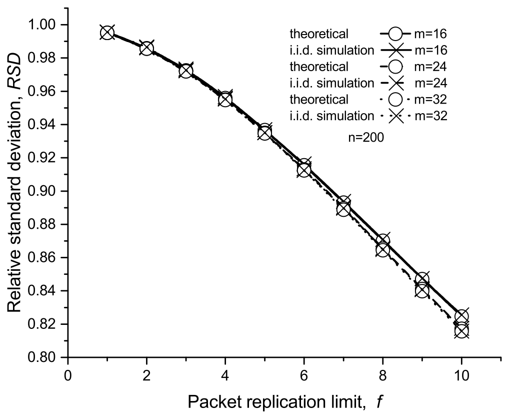


(b) RSD versus n

Fig. 8. The impact of number of nodes n on packet delivery delay performance in 2D MANET



(a) $E\{a_1\}$ versus f



(b) RSD versus f

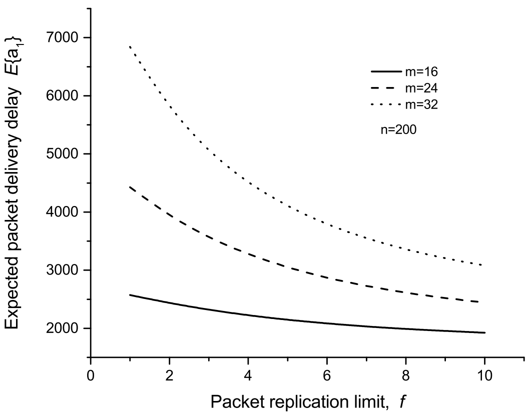
Fig. 9. The impact of packet replication limit f on packet delivery delay performance in 3D MANET

theoretical models, although were developed for the packet delivery delay performance under the i.i.d. mobility model, can also be used to predict the packet delivery delay performance in 3D MANETs under the random walk mobility model and random waypoint mobility model.

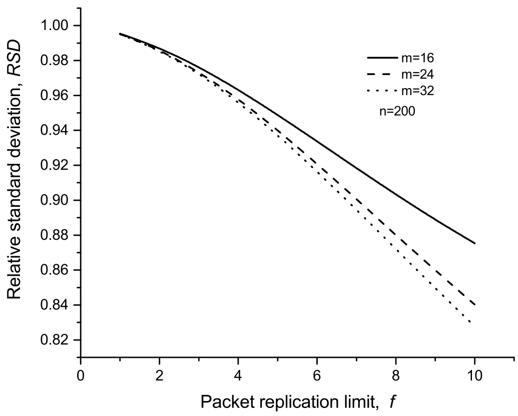
C. Performance Analysis

We first explore how the packet delivery delay performance $(E\{a_1\}, RSD)$ varies with the number of nodes n. As shown in Fig. 7, for each setting of f, as n increases, the expected packet delivery delay first decreases, and then increases. This can be explained as follows: when n is relatively small, the network is sparse and the increasing of n could lead to the increasing of the probability that a packet is transmitted out and thus decreases the packet delivery delay. As n further increases, the network nodes become relatively densely distributed and the negative effects of interference and medium contention issues begin to dominate the delivery performance, and thus the packet delivery delay increases. We can see from Fig. 7 that the simulated results under the i.i.d. mobility model match nicely with the theoretical ones. This further validates our theoretical models.

We proceed to explore how the packet delivery delay varies with packet replication limit f. We can see from Fig. 9 that the expected packet delivery delay decreases with f. This is because as f increases, the opportunity that destination node receives a packet will increase, and thus reducing the packet delivery delay. A further careful observation of Fig. 9(a) indicates that for each setting of f, a bigger m could result in a bigger packet delivery delay. It can be explained as follows: we know that the considered network area is divided into m^3 cells and the mobile nodes roam from one cell to another, which results in the nodes sparsely distributed in the network as m increases, and thus the packet delivery delay increases. Different from that of the performance $E\{a_1\}$, we can see from Fig. 9(b) that the behavior of RSD is very similar for all the settings of m. Fig. 9 also shows that the simulated results under the i.i.d. mobility model match nicely with the



(a) $E\{a_1\}$ versus f



(b) RSD versus f

Fig. 10. The impact of packet replication limit f on packet delivery delay performance in 2D MANET

theoretical ones.

D. Performance Comparison

In this subsection, we compare the packet delivery delay performance in 3D MANET with that in 2D MANET. Specifically, we choose a well-known cell-partitioned 2D MANET [23] and adopt two-hop relay algorithm for packet routing. The corresponding results in 2D MANET are summarized in Figs. 8 and 10.

For the same setting of these parameters in Figs. 7 and 8, and also in Figs. 9 and 10, these figures show that the expected packet delivery delay in 3D MANET is much bigger than that in 2D MANET. This phenomenon can be explained as follows. Recalling that in 3D MANET, the considered network area is evenly divided into m^3 cells, while in 2D MANET, the number of cells is m^2. Under the same setting of the number of nodes n, a larger value of the number of cells leads to a lower node density (i.e., $n/$the number of cells). Thus the nodes in 3D MANET is much more sparsely distributed than those in 2D MANET. Since the packet delivery speed becomes lower in a more sparsely distributed network, the expected packet delivery delay in 3D MANET is much bigger than that in 2D MANET. It also demonstrates that the packet delivery delay performance in 3D MANET is different with that in 2D MANETs. Thus, it is proved that the packet delivery delay performance indeed requires to be analyzed differently for 3D MANETs.

VIII. Conclusion

In this paper, we first develop a Markov chain theoretical framework to depict the packet delivery process under two-hop relay algorithm with packet replication. With the help of the Markov chain theoretical framework, we then derive closed-form expressions for mean and relative standard deviation of packet delivery delay. Simulation results indicate that our theoretical models can accurately predict packet delivery delay performance in 3D MANETs. Remarkably, our theoretical results indicate that packet replication technique can reduce the packet delivery delay. One interesting direction is to further extend the study of this paper to explore the impact of channel data rate, packet size and path loss issues on the packet delivery delay performance.

Appendix A
Proof of the Lemmas 1 and 2

Proof of Lemma 1:. The source node S conducts a Source-to-Destination transmission if the following three events happen simultaneously: S is in an active cell, S is selected as the transmitter, and the node D is either in the same cell with S or in one adjacent cell of S. The third event includes following two mutually exclusive cases: both S and D are inside this cell; or the S is inside this cell while the D is inside one of the 26 adjacent cells of this cell. We assume that apart from the nodes S and D, there are k other nodes inside this cell, $k \in [0, n-2]$, the probability that the node S is selected as the transmitter is $\frac{1}{k+2}$ (resp. $\frac{1}{k+1}$) under the former case (resp. under the latter case). Summing up the probabilities under these two cases, then we have

$$\begin{aligned}
p_{sd} &= \frac{1}{\alpha^3}\Big\{\sum_{k=0}^{n-2}\binom{n-2}{k}\Big(\frac{1}{m^3}\Big)^k\Big(\frac{m^3-1}{m^3}\Big)^{n-2-k}\frac{1}{m^3}\frac{1}{k+2} \\
&\quad+\sum_{k=0}^{n-2}\binom{n-2}{k}\Big(\frac{1}{m^3}\Big)^k\Big(\frac{m^3-1}{m^3}\Big)^{n-2-k}\frac{26}{m^3}\frac{1}{k+1}\Big\} \\
&= \frac{1}{\alpha^3}\Big\{\sum_{k=0}^{n-2}\binom{n-1}{k+1}\Big(\frac{1}{m^3}\Big)^{k+1}\Big(\frac{m^3-1}{m^3}\Big)^{n-2-k}\frac{1}{k+2} \\
&\quad-\sum_{k=0}^{n-2}\binom{n-2}{k+1}\Big(\frac{1}{m^3}\Big)^{k+1}\Big(\frac{m^3-1}{m^3}\Big)^{n-2-k}\frac{1}{k+2} \\
&\quad+\sum_{k=0}^{n-2}\binom{n-2}{k}\Big(\frac{1}{m^3}\Big)^{k+1}\Big(\frac{m^3-1}{m^3}\Big)^{n-2-k}\frac{26}{k+1}\Big\} \\
&= \frac{1}{\alpha^3}\Big\{\frac{27-m^3}{n-1}+\frac{m^3}{n}-\frac{26}{n-1}\Big(\frac{m^3-1}{m^3}\Big)^{n-1} \\
&\quad+\Big(\frac{m^3}{n-1}-\frac{m^3}{n}\Big)\Big(\frac{m^3-1}{m^3}\Big)^{n}\Big\} \qquad (26)
\end{aligned}$$

Notice that $\binom{n}{r} = \binom{n+1}{r+1} - \binom{n}{r+1}$ and $\frac{1}{r+1}\binom{n}{r} = \frac{1}{n+1}\binom{n+1}{r+1}$. So the formula (4) follows.

Similarly, the S conducts a Source-to-Relay or Relay-to-Destination transmission if the following four events happen concurrently: S is in an active cell, S is selected as the transmitter, there is at least one other node (except S and D) in the same cell of S or its 26 adjacent cells, and the node D is in one of the other $m^3 - 27$ cells(excluding this cell and its 26 adjacent cells). The probability that the D is in one of the other $m^3 - 27$ cells is $\frac{m^3-27}{m^3}$. The third event includes the following two mutually exclusive cases: this cell contains only node S; or this cell contains at least one other node aside from node S. If we suppose that there are k ($k \in [1, n-2]$) other nodes inside this cell (resp. the 26 adjacent cells of this cell), then the other $n - 2 - k$ nodes can be in any cell of the other $m^3 - 1$ (resp. $m^3 - 27$) cells. Summing up the probabilities under these two cases, then we have

$$p_{srd} = \frac{m^3 - 27}{m^3\alpha^3}\Big\{\sum_{k=1}^{n-2}\binom{n-2}{k}\Big(\frac{1}{m^3}\Big)^k\Big(\frac{m^3-1}{m^3}\Big)^{n-2-k}\frac{1}{k+1} + \sum_{k=1}^{n-2}\binom{n-2}{k}\Big(\frac{26}{m^3}\Big)^k\Big(\frac{m^3-27}{m^3}\Big)^{n-2-k}\Big\} \quad (27)$$

Proof of Lemma 2: In the next time slot, the destination node D may receive a packet either from the source node S or from one of the $g - 1$ relay nodes. Notice that these events are mutually exclusive , the probability that D receives a packet from S is p_{sd}, and the probability that D receives a packet from a single relay node is $\frac{p_{srd}}{2(n-2)}$. By summing up the probabilities of these events, the formula (6) follows. Similarly, in the next time slot the node S may transmit out a packet to any one of relay nodes. Notice that these events are also exclusive, and the probability that S transmits out a packet to a single relay node is $\frac{p_{srd}}{2(n-2)}$, so the formula (7) follows.

To derive $P_{sim}(g)$, let's focus on a specific relay node R which carries a copy of the packet and a specific relay node V which does not carry any copy of the packet. We use $P(S \to V, R \to D)$ to denote the probability that a Source-to-Relay transmission from S to V and a Relay-to-Destination transmission from R to D happen simultaneously in the next time slot. Thus the $P_{sim}(g)$ can be determined as

$$P_{sim}(g) = P(S \to V, R \to D) \quad (28)$$

First, we consider the active cell with node R. The R can conduct a Relay-to-Destination transmission with D only under the following two mutually exclusive cases: D is in this cell or D is in one of the 26 adjacent cells. We suppose that except the S, D, R, V, and the destination node of R's local traffic, there are in total k other nodes in the one-hop neighborhood of R, $k \in [0, n-5]$, among them i nodes are in the same cell as R, $i \in [0, k]$, and the other $k - i$ nodes are in the 26 adjacent cells. Then the probability that R and D are selected as the transmitter and the receiver, respectively, is $\frac{1}{(i+2)(k+1)}$ (resp. $\frac{1}{(i+1)(k+1)}$) under the former case (resp. under the latter case). Summing up the probabilities under these two cases, then we get the corresponding probability of the Relay-to-Destination transmission $R \to D$. Similarly, we can also get the probability of the Source-to-Relay transmission $S \to V$. Multiplying two probabilities corresponding to Source-to-Relay and Relay-to-Destination transmission, and then we have

$$P_{sim}(g) = \frac{(g-1)(n-g-1)(m^3-\alpha^3)}{4m^3\alpha^6}\sum_{k=0}^{n-5}\binom{n-5}{k} \cdot\Big(\sum_{i=0}^{k}\binom{k}{i}\frac{1}{k+1}\Big(\frac{1}{i+2}+\frac{26}{i+1}\Big)\Big(\frac{1}{m^3}\Big)^{i+1}\Big(\frac{26}{m^3}\Big)^{k-i}\Big) \cdot\sum_{t=0}^{n-4-k}\binom{n-4-k}{t}\Big(\sum_{l=0}^{t}\binom{t}{l}\frac{1}{t+1}\Big(\frac{1}{l+2}+\frac{26}{l+1}\Big) \Big(\frac{1}{m^3}\Big)^{l+1}\Big(\frac{26}{m^3}\Big)^{t-l}\Big)\Big(\frac{m^3-54}{m^3}\Big)^{n-4-k-t} \quad (29)$$

Notice that

$$\begin{aligned}
&\sum_{i=0}^{k}\binom{k}{i}\frac{1}{k+1}\Big(\frac{1}{i+2}+\frac{26}{i+1}\Big)\Big(\frac{1}{m^3}\Big)^{i+1}\Big(\frac{26}{m^3}\Big)^{k-i}\\
&=\sum_{i=0}^{k}\binom{k+1}{i+1}\frac{1}{k+1}\frac{1}{i+2}\Big(\frac{1}{m^3}\Big)^{i+1}\Big(\frac{26}{m^3}\Big)^{k-i}\\
&-\sum_{i=0}^{k}\binom{k}{i+1}\frac{1}{k+1}\frac{1}{i+2}\Big(\frac{1}{m^3}\Big)^{i+1}\Big(\frac{26}{m^3}\Big)^{k-i}\\
&+\sum_{i=0}^{k}\binom{k}{i}\frac{1}{k+1}\frac{26}{i+1}\Big(\frac{1}{m^3}\Big)^{i+1}\Big(\frac{26}{m^3}\Big)^{k-i}\\
&=\frac{1}{(k+1)(k+2)}\Big\{27\Big(\frac{27}{m^3}\Big)^{k+1}-(k+10)\Big(\frac{26}{m^3}\Big)^{k+1}\Big\}\\
&-\frac{1}{(k+1)^2}\Big\{26\Big(\frac{27}{m^3}\Big)^{k+1}-(k+9)\Big(\frac{26}{m^3}\Big)^{k+1}\Big\}\\
&+\frac{26}{(k+1)^2}\Big\{\Big(\frac{27}{m^3}\Big)^{k+1}-\Big(\frac{26}{m^3}\Big)^{k+1}\Big\}\\
&=\frac{27(\frac{27}{m^3})^{k+1}-26(\frac{26}{m^3})^{k+1}}{(k+1)(k+2)}
\end{aligned} \quad (30)$$

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