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A Coalitional Game Theoretical Model for Content Downloading in Multihop VANETs

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***Abstract*—Vehicular ad hoc networks (VANETs) are viewed as an effective way to disseminate content among vehicles on the road. While most of the current research efforts in VANETs focus on improving the packet delivery performance, only limited work aims to provide cost-efficient solutions for content downloading. This paper proposes a novel approach for the vehicles to download a common content in a cost-efficient way. The basic idea is to stimulate the vehicles to download the content cooperatively in mutually disjoint coalitions. To study the cooperation among the vehicles, a coalitional game model is proposed. Moreover, a distributed coalition formation algorithm is designed to obtain a stable coalition structure and minimize the total communication cost. Numerical results show that the proposed content download approach can achieve a considerable communication cost reduction compared with the non-cooperative case.**

I. Introduction

Nowadays vehicular ad hoc networks (VANETs) [1] are studied intensively in academia and industry. As an important part of the intelligent transport system (ITS), VANETs will bring convenient and efficient driving experience to the drivers in the near future. By using vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications, there could be considerable number of useful applications [2] provided by VANETs. These applications can be safety applications, or user applications [3], both of which need to download large numbers of content from the roadside infrastructure or even through the Internet, such as accident warnings, current traffic conditions, updated electronic maps, multimedia files, etc.

However, there are four main factors which may reduce the download performance in vehicular networks. The first one is the dynamic topology. Due to the diversity of node velocities, the link between two vehicles is short-lived and hard to maintain. The mobility can brings another factor: channel fading and impairments, which lead to sever packet losses. The third one is the disrupted connectivity, which occurs in a scenario where the vehicles are distributed sparsely. The fourth factor is the limited bandwidth. Since the vehicles may get a very high density in a city scenario or a multi-lane highway in rush hours, if there are a large number of data transmitted through the network, each vehicle node may suffer intense channel contention. Thus the bandwidth is a scare resource in VANETs.

Most of the previous work for content downloading in VANETs aims to overcome the impact of mobility, channel fading and disrupted connectivity. These proposed methods fall into two categories. The first one is optimizing infrastructure deployment, such as obtaining the maximum distance between RSUs and guarantee the delay under a bound [4], or maximizing the contact opportunity and improve the average throughput through the roadside units [5]. The second category is improving content delivery performance. Some work uses network coding to reduce download time [6] [7], and some authors use cooperative vehicle-to-vehicle communications to increase data delivery ratio such as multicast epidemic data dissemination [8] and gossip [9]. There is also some work using peer-to-peer file sharing [10] [11], static nodes in intersections [12] or parked cars [13] to achieve better download performances. However, none of the previous work aims to reduce the total communication cost, which saves the limited bandwidth equivalently.

This paper studies the problem of cost-efficient content downloading in multihop VANETs in a view of coalitional game theory. On one hand, the proposed coalitional game enables the vehicles to form cooperative and mutually disjointed groups (also called coalitions) to download and share the content, since the vehicles tend to get the content form its one or two-hop neighbours instead of further RSUs. On the other hand, the vehicles can make individual decisions to join or leave a given coalition to minimize the total communication cost. The total cost contains two parts, the first one is for multihop content transmissions, the second part is for coalition formation and maintenance. Our main contributions are summarized as follows:

1) The multihop transmission cost is modelled and mathematically analysed, which considers the mobility of the vehicles and the transmission duration.
2) A greedy algorithm is designed to distribute the content and get the value function of each coalition.
3) A distributed coalition formation algorithm is designed to enable the vehicles to form a stable network partition with disjoint coalitions in order to minimize the total communication cost.
4) The advantage of the proposed approach is verified in a comprehensive simulation.

The remainder of this paper is organized as follows: Section II provides the system model. Section III presents the detailed

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procedure of the coalitional game model. Numerical results is shown in section IV. Section V concludes the paper. The proofs of theorems are given in the Appendix.

II. System Model

A. Mobility and Communication Model

The abstract network is shown in Fig.1, where two RSUs (RSU 1 and RSU 2) are built along a bidirectional highway. The segment between the RSUs has a length of L, and there are in total m vehicles travelling in the segment, thus the traffic density can be expressed as $\rho = m/L$, defined as cars per meter. The positive direction is from RSU2 to RSU1. Suppose the position of RSU 2 is 0 and the position of RSU 1 is L, the position of each vehicle lies in $[0, L]$.

The m vehicles are uniformly distributed on the highway segment, the probability density function (pdf) of vehicle i's position $\mathcal{X}_i$ can be derived:

$$f_{\mathcal{X}_i}(x) = \begin{cases} \frac{1}{L}, & 0 \le x \le L \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

Suppose the speed of each vehicle is independently uniformly distributed in $[v_{min}, v_{max}]$, when the positive direction is given, vehicle i's velocity $\mathcal{V}_i$ can be positive or negative, the pdf of its magnitude is:

$$f_{|\mathcal{V}_i|}(v) = \begin{cases} \frac{1}{v_{max} - v_{min}}, & v_{min} \le |v| \le v_{max} \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

Equipped with wireless devices, each vehicle has the same transmission range R as the RSUs. Using a Rayleigh fading model, the probability of successful transmission for a packet from node n_i to n_j can be expressed as the probability of having a link above the target SNR γ_0 at the receiver [14]:

$$P_{n_i,n_j} = exp\left(-\frac{\gamma_0 * N_0 * (d_{n_i,n_j})^\alpha}{K * P_m}\right) \quad (3)$$

where N_0 means the Gaussian noise, d_{n_i,n_j} is the Euclidean distance of n_i and n_j, α is the path loss exponent, K is a path loss constant, and P_m is the transmission power of the sender (Suppose each node has the same transmission power).

B. Coalitional Game Theory

Suppose there are $|N|$ vehicles in total which is interested in a common content in RSUs. These vehicles are called the $players$. The players set is $N = (1, \ldots, |N|)$. We have the following definition [15]:

Definition 1. *A coalitional game with transferable utility (TU) is defined by a unique pair (N, V) where N is the players set, and V is a value function over the real line defined as $v : 2^N \to \mathbb{R}$ such that for every coalition $S \subseteq N$, $V(S)$ is a real number and can be divided in any manner between the coalition members.*

In each coalition, there are two types of players. The first type is called $seed\ player$, while the second one is $normal\ player$. Both of the two types can share their downloading content to other coalition members, but the seed can only download from the RSUs while the normal players can get the content form the seed or other normal players. There is only one seed in coalition S, expressed as $n_{seed}(S)$.

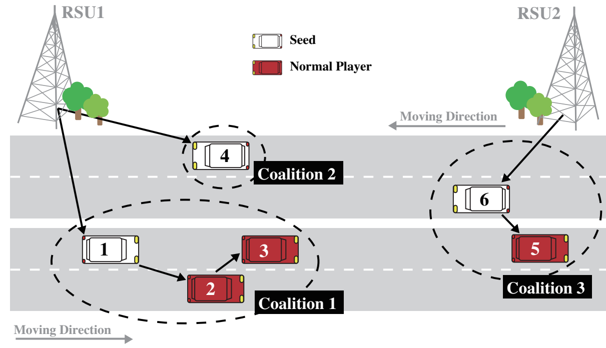

Fig. 1. An example of coalitions in content downloading

As Fig.1 shows, there are 3 disjoint coalitions with their seeds (player 1, 4, and 6). Note that the arrows in Fig.1 are not links, but paths where there may be intermediate nodes along each path.

III. Coalitional Game for Content Downloading

A. Communication Cost for Multihop Transmissions

In this paper the communication cost for multihop transmission is defined as the average expectation of the transmission times for each packet, it is determined by five factors about the pair of sender and receiver: hop count, single hop transmission times, initial distance, relative velocity and the transmission duration time.

We use $P_k(x)$ as the probability of the event that two vehicles with an Euclidean distance x are a k-hop neighbor of each other. According to [16], this probability can be mathematically expressed as:

$$\begin{aligned} P_k(x) = &\left(1 - \sum_{i=1}^{k-1} P_i(x)\right) * \\ &\left(1 - exp(-\int_{x-R}^{x} P_{k-1}(s) \cdot P_1(x-s)\rho ds)\right) \end{aligned} \quad (4)$$

where ρ is the traffic density and R is the transmission range. Also there is:

$$P_1(x) = \begin{cases} 1, & x \le R \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

Here a random variable $\mathcal{K}_x$ is used to express the hop count between two nodes with a distance x. According to (4)(5), the expectation of $\mathcal{K}_x$ is a function of x:

$$E[\mathcal{K}_x] = \sum_{k=1}^{+\infty} k \cdot P_k(x) \quad (6)$$

Another random variable $\mathcal{E}$ is used to express the transmission times for one packet in a single hop, which is the reciprocal of the probability of a successful transmission given in (3):

$$\mathcal{E} = exp\left(\frac{\gamma_0 * N_0 * (\mathcal{Y})^\alpha}{K * P_m}\right) \quad (7)$$

Where $\mathcal{Y}$ is a random variable defined as the Euclidean distance between the one-hop sender and receiver, since all the vehicles are uniformly distributed along the road, $\mathcal{Y}$ is also a uniformly distributed variable in the interval $[0, R]$ with a pdf as:

$$f_\mathcal{Y}(y) = \begin{cases} \frac{1}{R}, & 0 \leq y \leq R \\ 0, & \text{otherwise} \end{cases} \quad (8)$$

From equation (6) and (7), the expected transmission times for one packet in a single hop is:

$$\begin{aligned} E(\mathcal{E}) &= \int_0^R exp\left(\frac{\gamma_0 * N_0 * y^\alpha}{K * P_m}\right) \cdot f_\mathcal{Y}(y) dy \\ &= \frac{1}{R}\int_0^R exp\left(\frac{\gamma_0 * N_0 * y^\alpha}{K * P_m}\right) dy \end{aligned} \quad (9)$$

The above findings are summarized as follows:

Lemma 1. *If random variable $\mathcal{I}_x$ is the transmission times for one packet which is transmitted along a path between two nodes with a distance x, then its expectation is:*

$$E[\mathcal{I}_x] = E[\mathcal{K}_x]E[\mathcal{E}] \quad (10)$$

Proof: See the appendix. ■

Theorem 1. *If there are two vehicles n_i and n_j with velocities v_i and v_j and initial positions x_i and x_j. During T seconds, n_i sends a content of n_p packets to n_j. The average expectation of the transmission times for each packet during the T seconds is:*

$$\overline{\mathcal{I}}_{ij} = \frac{1}{T}E(\mathcal{E})\int_0^T \sum_{k=1}^{+\infty} k \cdot P_k(|\Delta x - \Delta v t|) dt \quad (11)$$

Where $\Delta x = x_i - x_j$, $\Delta v = v_i - v_j$.

Proof: See the appendix. ■

Here $\overline{\mathcal{I}}_{ij}$ is used to express the multihop transmission cost, which measures the cost of sending one packet to the destination during the content downloading process.

B. Value Function of A Given Coalition

For a given coalition S, we aim to find the best way to distribute the content, which means selecting the proper seed $n_{seed}(S)$ and planning the transmission path among the players. All the players in coalition S and the two RSUs (1 and 2) form a graph $\mathcal{G}$, the weight of each edge of $\mathcal{G}$) is the transmission cost between them:

$$w(e_{i,j}) = \overline{\mathcal{I}}_{ij} \quad (12)$$

Now the problem is how to find a minimum cost spanning tree ($\mathcal{T}(\mathcal{G})$) with only one node linking directly to the root(the RSU1 or RSU2). Here we use $\mathcal{T}^*(S)$ as the minimum spanning tree[1] of coalition S and $W(\mathcal{T})$ is the total weight of a tree $\mathcal{T}$, the following theorems can be derived:

Lemma 2.

$$W(\mathcal{T}(\mathcal{G})) = \min\left(w(e_{1,n_{seed}}), w(e_{2,n_{seed}})\right) + W(\mathcal{T}^*(S)) \quad (13)$$

Where

$$n_{seed}(S) = \arg\min_{i \in S}\left(\min(w(e_{i,1}), w(e_{i,2}))\right) \quad (14)$$

Proof: There are two steps to construct $\mathcal{T}(\mathcal{G})$, the first step is finding an edge combining S and one of the RSUs, which means to select $n_{seed}(S)$. The second step is finding a spanning tree within the coalition S, which express the process of content sharing after the seed downloads the content form one of the RSUs. If both of the two steps minimize the weights, the overall weight will be minimized. Since the solution of the second step is finding a minimum spanning tree of S, it is obvious that the solution of the first step is finding a node with the minimum weight to its nearest root (RSU) node. ■

Here a utility function $U(S)$ is defined as the gain achieved by coalition S, from equation (12) to (14), it is given by:

$$U(S) = \begin{cases} -W(\mathcal{T}(\mathcal{G})) & \text{if } S \neq \varnothing \\ 0 & \text{otherwise} \end{cases} \quad (15)$$

Note that a minus sign is inserted to turn the problem into a maximization problem.

To form and maintain a coalition, the players may exchange their local information, which brings additional cost. Thus the cost function of coalition S is expressed as:

$$C(S) = \beta(|S| - 1)\left(\frac{max(d_{ij})}{L} + \frac{\sigma_v}{\overline{v}}\right) \qquad i, j \in S \quad (16)$$

Where β is a cost-coefficient, $max(d_{ij})$ is the largest distance between two players in a coalition, which measures the communication area of the coalition. L denotes the distance of the two RSUs. σ_v is the standard deviation of the velocities. $\overline{v}$ is the average speed of all the vehicles, according to equation (2), it is given by $\overline{v} = \frac{v_{max} + v_{min}}{2}$.

The cost function above shows that if a coalition has a large size, a large communication area, or if the diversity of the velocities is great, the cost for the coalition formation and maintenance will be a large number, since a large size of coalition and communication area call for more communication cost, and a great diversity of velocities make it harder to maintain a transmission path in a dynamic topology. (16) also shows if $|S| = 1$, $C(S) = 0$.

Using $U(S)$ and $C(S)$, the value function $V(S)$ of coalition S can be derived as follows:

$$V(S) = U(S) - C(S) \quad (17)$$

[1]There are some algorithms to find a minimun tree of a connected graph, such as Prim algorithm and Kruskal algorithm, here all of them are feasible.

Since the coalition game proposed is a TU game, which means the value of a coalition can be divided among its members. Using an individually rational egalitarian rule, the individual payoff $\phi_i(S)$ of each player i is given as follows:

$$\phi_i(S) = \frac{1}{|S|}\left(V(S) - \sum_{i \in S} V(\{j\})\right) + V(\{i\}) \tag{18}$$

where $V(\{i\})$ and $V(\{j\})$ are individual payoffs of i and j in a non-cooperative scenario.

Finally the total communication cost of coalition S can be defined as the opposite number of the cost function:

$$C_T = -V(S) \tag{19}$$

The above findings are summarized as **Algorithm 1**, which uses a greedy algorithm to select the seed and to compute the value for a given coalition S.

Algorithm 1 Greedy Seed Selection and Value Computing

```
Compute w(e_{i,j}) for any pair of players i, j in S by (4)-(12).
Find the minimum spanning tree T*(S).
n_seed(S) ← arg min(min(w(e_{i,1}), w(e_{i,2}))), i ∈ S.
Calculate the total weight T(G) by equation (13)(14).
Get V(S) by (7)-(10)
```

C. Distributed Coalition Formation Algorithm

While we study content delivery in a given coalition in section III-B, in this section we show how to form the disjoint coalitions. There are quantities of approaches to build a coalition formation algorithm which are studied recently [17] [18]. Before building the algorithm, some concepts are given as follows.

A $collection$ of coalitions in the grand coalition N, denoted S, is defined as the set $\Gamma = \{S_1, \ldots, S_l\}$ of mutually disjoint coalitions $S_i \subseteq N$. Thus a collection is any arbitrary group of disjoint coalitions S_i of N not necessarily spanning all players of N. If the collection spans all the players of N, i.e, $\bigcup_{j=1}^{l} S_j = N$, the collection is called a $partition$ of N.

The goal of the coalition formation algorithm is to find the best partition where the total value of N is maximized. For a given set N where $|N| = n$, the total number of possible partitions D_n is the $Bell\ Number$ of n:

$$D_n = \sum_{j=0}^{n-1} \binom{n-1}{j} D_j \tag{20}$$

for $n \geq 1$ and $D_0 = 1$. Since the Bell Number D_n will be very large as n increases ($D_{10} = 115,975$), finding the best partition through comparing all the D_n possible partitions is infeasible because of the high computation complexity.

Another important concept is the $utilitarian\ order$. A utilitarian order $\triangleright$ is defined for comparing two partitions $\Gamma_1 = \{R_1, \ldots, R_l\}$ and $\Gamma_2 = \{S_1, \ldots, S_p\}$ of N such that $\Gamma_1 \triangleright \Gamma_2$ means the way Γ_1 partitions N is preferred to the way Γ_2 partitions N, if the total social welfare achieved in Γ_1 is strictly greater than in Γ_2, i.e, $\sum_{i=1}^{l} V(R_i) > \sum_{j=1}^{p} V(S_j)$.

In [19], the authors provide two generic rules that can be utilized to derive coalition formation algorithms for different application scenarios. These two rules use the utilitarian order for forming and breaking coalitions, which are defined as follows:

Definition 2 (Merge Rule)**.** *Any set of coalitions* $\{S_1, \ldots, S_l\}$ *may merge as* $\{S_1, \ldots, S_l\} \rightarrow \left\{\bigcup_{j=1}^{l} S_j\right\}$, *if* $\left\{\bigcup_{j=1}^{l} S_j\right\} \triangleright \{S_1, \ldots, S_l\}$.

Definition 3 (Split Rule)**.** *Any one coalition may split as* $\left\{\bigcup_{j=1}^{l} S_j\right\} \rightarrow \{S_1, \ldots, S_l\}$, *if* $\{S_1, \ldots, S_l\} \triangleright \left\{\bigcup_{j=1}^{l} S_j\right\}$.

Using the above merge and split rule, the proposed coalition formation algorithm is shown in **Algorithm 2**. Initially, the player set N is partitioned by a non-cooperative manner. For simplicity each merge-and-split iteration only allows the operation of two coalitions, which means each time only two coalitions can merge into a new one, or one coalition can only split into two new coalitions. Through merge-and-split iterations, the partition of the players finally converges to a stable one, as shown in **Theorem 2**.

Algorithm 2 Distributed Coalition Formation Algorithm

```
All the players start in a non-cooperative manner with partition Γ = {1, 2, ..., n}.
The players start to find the others in the network through broadcasting or using beacons.
loop  For each player
    Randomly select two coalitions of Γ: S_i and S_j
    if {S_i ∪ S_j} ▷ {S_i, S_j} then
        Γ ← (Γ \ {S_i, S_j}) ∪ (S_i ∪ S_j)
    end if
    Randomly select one coalition of partition Γ: S_c
    Randomly select S_k and S_k where S_c = S_k ∪ S_l,
  S_k ∩ S_l = ∅, S_k ≠ ∅, S_l ≠ ∅
    if {S_k, S_l} ▷ {S_k ∪ S_l} then
        Γ ← (Γ \ {S_c}) ∪ {S_k, S_l}
    end if
end loop  When the partition converges to Γ_final
Each RSU disseminates the content to every seed.
Each n_seed shares the content with its coalition members using T*(S) in an online mode.
```

Theorem 2. *The merge-and-split based coalition formation algorithm converges to a final partition* Γ_{final} *starting from any partition* Γ_{intial}*:*

$$\Gamma_{initial} \rightarrow \ldots \rightarrow \Gamma_k \rightarrow \ldots \rightarrow \Gamma_{final} \tag{21}$$

Proof: See [20] for the proof. ■

IV. Numerical Results

For simulation, a bidirectional 4-lane highway segment is considered. The length of the segment is $L = 1$ km. The

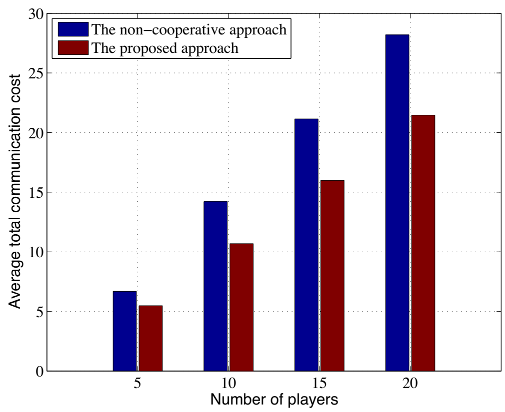

Fig. 2. The total communication cost vs. the number of requesting vehicles n

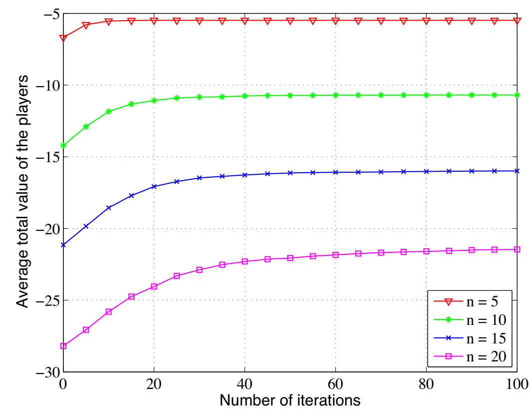

Fig. 3. The total value of the players vs. merge and split iterations

number of vehicles travelling along the segment is $m = 50$, half of them moves in the positive direction, and the traffic density is $\rho = 0.05$ car/meter. The velocities of the vehicles are uniformly distributed in $[20, 30]$.The number of players varies from 5 to 20, these players are randomly chosen among the 50 vehicles. The transmission range of each vehicle is set to $R =$ 300 meters. The threshold SNR γ_0 is 10 db, while the noise level N_0 is -120 db. The path loss constant is set to $K = 1$, the path loss exponent α is 3, and the transmission power P_m for each vehicles is 23 dbm. The content transmission duration is set to $T = 10$ seconds. Since the vehicles are randomly distributed, the simulation repeats for 100 times and the total cost is computed and averaged.

Firstly we study the total communication cost in the content download process versus the number of requesting vehicles (the players). The results are in Figure 2. It shows that as the number of the players increases, the total cost increases as well in both coalitional and non-cooperative cases. However, the proposed coalitional game can achieve a significant cost reduction up to 25% compared with the non-cooperative case under the same number of players, this is because our approach can reduce unnecessary transmissions through the cooperation of the vehicles.

We also study the total value of the players versus the merge and split iterations. Figure 3 shows as the iteration increases, the total value of the players keeps rising until it reaches a stable value, which means the partitions of the players finally converges to a stable one. Figure 3 also indicates that more players lead to more merge-and-split iterations to the convergent value, since a set of more members has more kinds of partitions, which needs longer iterations to reach the stable partition.

Finally we study the variance of the number of coalitions in a game with different cost-coefficients. Figure 4 indicates that a larger cost-coefficient leads to a larger number of coalitions. As the cooperation cost increases, less players tend to download the content in a cooperative manner, each coalition will have a smaller size, thus the number of coalitions increases. Figure 4 also shows the more players in a game leads to more of coalitions in a game, since the cooperation cost also increases as the number of players.

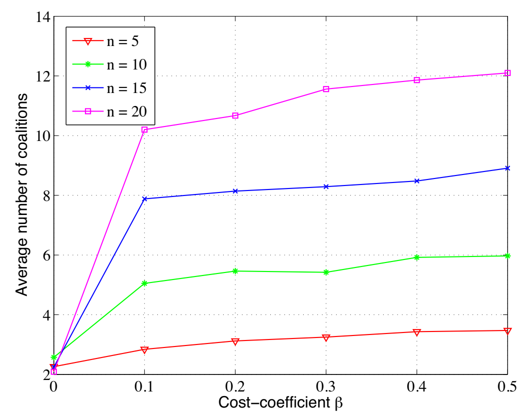

Fig. 4. The number of coalitions in a game vs. cost-coefficient

V. Conclusion

In this paper we propose a coalitional game theoretical model to reduce the communication cost of content downloading in multihop VANETs. The model enables the vehicles to download the content in a cooperative manner where the cost of cooperation is also considered. Numerical results verifies that the proposed model can reduce the total communication cost significantly during the downloading process. The convergence of the proposed coalition formation algorithm is also analysed. In addition, the impact of coalition formation cost is studied, showing that the number of coalitions in a game has a positive correlation with the cooperation cost.

APPENDIX
PROOF OF THE THEOREMS

Proof of Lemma 1: Let $\mathcal{E}_i$ donate the transmission time of the i th hop along the multihop route, $i = 1, 2, \ldots$, then $\mathcal{I}_x$ can be expressed as $\sum_{i=1}^{\mathcal{K}_x} \mathcal{E}_i$, here $\mathcal{E}_i$ and $\mathcal{K}_x$ are independent, $\mathcal{E}_i$ and $\mathcal{E}$ has the same distribution. Then

$$E[\sum_{i=1}^{\mathcal{K}_x} \mathcal{E}_i] = E[E[\sum_{i=1}^{\mathcal{K}_x} \mathcal{E}_i | \mathcal{K}_x]]$$

Since

$$E[\sum_{i=1}^{\mathcal{K}_x} \mathcal{E}_i | \mathcal{K}_x = k] = E[\sum_{i=1}^{k} \mathcal{E}_i | \mathcal{K}_x = k]$$
$$= E[\sum_{i=1}^{k} \mathcal{E}_i] = kE[\mathcal{E}]$$

Which deduces

$$E[\sum_{i=1}^{\mathcal{K}_x} \mathcal{E}_i | \mathcal{K}_x] = \mathcal{K}_x E[\mathcal{E}]$$

Thus

$$E[\mathcal{I}_x] = E[\sum_{i=1}^{\mathcal{K}_x} \mathcal{E}_i] = E[\mathcal{K}_x E[\mathcal{E})]] = E[\mathcal{K}_x] E[\mathcal{E}]$$

■

Proof of Theorem 1: Suppose $\mathcal{I}_t$ is the total transmission times of the packets during a transmission time T, where each packet has the same slot $\Delta t = \dfrac{T}{n_p}$. Since $\mathcal{I}_t = \sum_{r=1}^{n_p} \mathcal{I}_{x_r}$,

$$E[\mathcal{I}_t] = E[\sum_{r=1}^{n_p} \mathcal{I}_{x_r}] = \sum_{r=1}^{n_p} E[\mathcal{I}_{x_r}]$$

By using equation (6) and (10),

$$E(\mathcal{I}_t) = \sum_{r=1}^{n_p} E[\mathcal{K}_{x_r}] E[\mathcal{E}]$$
$$= E[\mathcal{E}] \sum_{r=1}^{n_p} (\sum_{k=1}^{+\infty} k \cdot P_k(x_r))$$
$$= E[\mathcal{E}] \sum_{r=1}^{n_p} (\sum_{k=1}^{+\infty} k \cdot P_k(|\Delta x - \Delta v \cdot r \cdot \Delta t|))$$

Then

$$\overline{\mathcal{I}} = \frac{E[\mathcal{I}_t]}{n_p} = \frac{E[\mathcal{I}_t \Delta t]}{T}$$
$$= \frac{1}{T} E[\mathcal{E}] \sum_{r=1}^{n_p} (\sum_{k=1}^{+\infty} k \cdot P_k(|\Delta x - \Delta v \cdot r \cdot \Delta t|)) \Delta t$$

Since Δt is very small, suppose $\Delta t \to 0$, then

$$\overline{\mathcal{I}} = \frac{1}{T} E[\mathcal{E}] \lim_{\Delta t \to 0} \sum_{r=1}^{n_p} (\sum_{k=1}^{+\infty} k \cdot P_k(|\Delta x - \Delta v \cdot r \cdot \Delta t|)) \Delta t$$
$$= \frac{1}{T} E(\mathcal{E}) \int_0^T \sum_{k=1}^{+\infty} k \cdot P_k(|\Delta x - \Delta v t|) dt$$

■

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