OPTIMAL CACHING IN CONTENT-CENTRIC MOBILE NETWORKS USING FILE SEGMENTATION

Trung-Anh Do, Ngoc Chu Quang and Bac Dang Hoai

Posts and Telecommunications Institute of Technology, Hanoi, Vietnam

Abstract: **In this paper, we study the throughput performance in a content-centric mobile ad hoc network, where each node moves using multihop according to the random walk mobility model and requests a file from the library independently at random, according to a Zipf popularity distribution. In our network model, we assume that each file consists of K distinct segments of equal size such that each of n mobile nodes is able to transmit completely one segment to one of its neighbor cells in one time slot. Using multihop transmission, the throughput scaling law is analyzed based on the following two reception strategies, which are introduced to determine how K distinct segments are fully delivered to the requesting node in turn to rebuild the desired file: A sequential reception and a random reception. Then, we analyze the throughput of the content-centric wireless networks and find the optimal cache allocation strategies analytically, which maximize the throughput. Our main result indicates that the throughput obtained from the random reception strategy outperforms the sequential reception case.**

Keywords: Caching, content-centric network, mobile ad hoc network, file segmentation, scaling law.

I. INTRODUCTION

Over last decade, Internet traffic has been increasing rapidly. Data caching [1], which brings contents closer to users, has emerged as a promising technique that deals with the exponential growth of internet traffic [2]. Thanks to the benefits of replicating popular contents across networks, caching techniques play an important role in maintaining the sustainability of future wireless networks.

As the number of users continues to grow dramatically, the capacity scaling law behavior has been widely studied in large wireless networks. In [3], Gupta and Kumar showed that, for a static ad hoc

network with n source—destination pairs randomly distributed in a unit area, the per-node throughput of the order of $\sqrt{\frac{\log n}{n}}$ is achievable using the nearest neighbor multihop transmission. Besides multihop transmission, there have been various research directions to improve the per-node throughput up to a constant scaling by using hierarchical cooperation [4] and node mobility [5][6].

Contrary to the studies on the conventional ad hoc network model in which source-destination pairs are given and fixed, investigating *content-centric ad hoc networks* would be quite challenging. As files are cached by numerous nodes over a network, finding the closest content holder of each request and scheduling between requests are of crucially importance for the overall network throughput. The scaling behavior of content-centric ad hoc networks has received a lot of attention in the literature [7-10]. In *static* ad hoc networks, throughput scaling laws were analyzed using multihop communications [7][8], which yields a significant performance gain over the single-hop caching scenario. In addition, in [9], performance on the throughput and delay was investigated for *mobile* ad hoc networks under various mobility models by showing that increasing the mobility degrees of nodes leads to worse performance. Such an analysis was extended to static and mobile hybrid networks with multiple base stations, [10][11], where the fluid model [6] allowing the size of each file to be arbitrarily small is adopted. Thus, the time required for transmitting a file is assumed to be much smaller than one time slot.

In addition, caching using file segmentation, which is a popular configuration of coded caching, was introduced in [12][13], where each file is formed by K encoded segments and each user downloads a part of K segments to rebuild the original file.

In this paper, we consider a content-centric mobile ad hoc network using file segmentation, where each node moves according to the random walk mobility model (RWMM) and requests a file from the library independently at random, according to a Zipf

popularity distribution. Specifically, instead of using the fluid model, we take into account the case where the size of each file is so large that it cannot be successfully transmitted in one time slot. Then, each file is divided into K distinct uncoded segments of equal (unit) size such that each of n mobile nodes is able to transmit completely one segment to one of its neighbor cells in one time slot. We introduce the following two reception strategies to decide how K distinct segments of a file are fully delivered to the requesting node: A sequential reception and a random reception. Based on the two reception strategies, the throughput scaling law is shown and optimized by finding analytically the optimal cache allocation strategies in terms of maximizing the throughput. Our main result indicates that the throughput obtained from the random reception strategy is superior to that of the sequential reception strategy.

We use the following asymptotic notation: i) $f(x) = O\big(g(x)\big)$ means that there exist constants C and c such that $f(x) \le Cg(x)$ for all $x > c$, ii) $f(x) = o\big(g(x)\big)$ means that $\lim_{x\to\infty}\frac{f(x)}{g(x)} = 0$, iii) $f(x) = \Omega\big(g(x)\big)$ if $g(x) = O\big(f(x)\big)$, iv) $f(x) = \Theta\big(g(x)\big)$ if $f(x) = O\big(g(x)\big)$ và $f(x) = \Omega\big(g(x)\big)$ [14].

II. NETWORK MODEL

We consider a content-centric mobile ad hoc network formed by n mobile nodes, which are assumed to be uniformly distributed into a unit torus. We adopt the random walk mobility model for the node's mobility pattern. In particular, the unit torus is divided into n square cells, i.e., the unit torus becomes a $\sqrt{n} \times \sqrt{n}$ discrete torus. The next location of a node located in the cell (i, j) will be in one of the four neighbor cells $(i-1, j)$, $(i, j-1)$, $(i+1, j)$, $(i, j+1)$ with equal probability. Thus, the given random walk model assumes that each node moves a distance $\frac{1}{\sqrt{n}}$ after each time slot.

We assume that the request probability of file $m \in \{1, \dots, M\}$ following a Zipf popularity distribution is given by $p_m = \frac{m^{-\alpha}}{H_\alpha(M)}$, where $H_\alpha(M) = \sum_{i=1}^{M} i^{-\alpha}$ and $\alpha > 0$ is the Zipf exponent. High values of α means that most of the requests are generated from a few most popular files.

In our work, instead of assuming that the sizes of files are arbitrarily small so that the time required for transmitting a file is much smaller than one time slot as in the fluid model, we adopt the segmented downloading technique for file transmissions. Specifically, each file is assumed to be divided into $K = \Theta\big(n^\beta\big)$ distinct uncoded segments of equal (unit) size, where $0 < \beta < 1$, such that each of n mobile nodes is able to completely transmit one segment to one of its four neighbor cells in each time slot. A segment received by a node in a given time slot cannot be transmitted by the node until the next time slot. Similar to the peer-to-peer content delivery system that implemented a kind of segmented downloading technology, the requesting node receives

the desired file after collecting all K desired segments and recombining the parts into the file. In our content-centric network, each node is assumed to be equipped with a local cache, which is installed to store at most $S = \Theta(K)$ distinct segments.

Consistently with the current information theoretic literature on caching networks, a caching scheme is formed by two phases: caching placement and delivery. Equivalently, the problem consists of storing files in the caches such that the delivery is as efficient as possible. We first describe the caching phase, which determines how to cache segments of files in the on-board memory of n nodes. Let $X_{m,i}$ denote the number of replicas of segment i of file $m \in \{1, \dots, M\}$. Similarly as in [7][9][11], we employ the *random caching* strategy such that $X_{m,i}$ replicas are distributed uniformly and at random over the caches in n nodes. Suppose that $X_{m,i} = X_m$ for all $i \in \{1, \dots, K\}$, where X_m is the number of replicas of file m in the network, we will drop the index i and denote $X_{m,i}$ by X_m. Note that in the delivery phase, the positions of X_m nodes storing segment i of file m will be changed independently and randomly over time due to the node mobility. In order for a cache allocation to be feasible, $\{X_m\}_{m=1}^{M}$ should satisfy the following total caching constraint:

$$\sum_{m=1}^{M} K X_m \le nS. \qquad (1)$$

Now, let us describe the delivery phase of the requested files, which allows the requested files to be delivered to the corresponding nodes over wireless channels. During the delivery phase, each node downloads its requested file (possibly via *multihop*) from one of the nodes storing the requested file in their caches. We adopt the *protocol model* [3] for successful content delivery. In particular, let $d(u, v)$ denote the Euclidean distance between nodes u and v. Then, content delivery from node u to node v is assumed to be successful if and only if $d(u, v) > r$ and there is no other active transmitter in a circle of radius $(1 + \nabla)r$ from node v, where r and $\nabla > 0$ are given protocol parameters.

III. CONTENT DELEVERY ROUTING IN MOBIE MULTIHOP NETWORKS
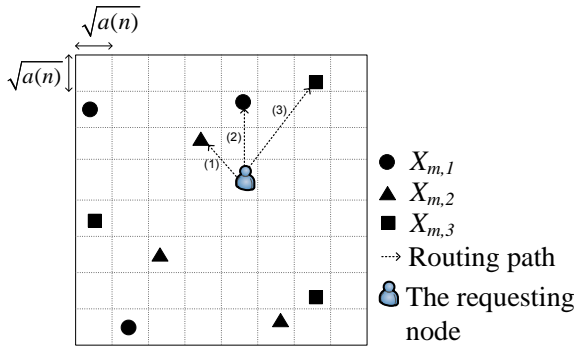
A. Reception strategies

In this subsection, we describe the two reception strategies illustrated in Fig. 1, which represents a way of how K segments of the desired file are delivered to the requesting node.

- *Sequential reception:* All K segments of a file are delivered in sequence. As illustrated in Fig. 1(a), the requesting node receives the first segment, denoted by $X_{m,1}$, of file m, the second segment $X_{m,2}$, and the third segment $X_{m,3}$ in sequence until it receives all K distinct segments of the desired file.

- *Random reception*: The requesting node receives the segments in an arbitrary way. As illustrated in Fig. 1(b), it first receives the second segment $X_{m,2}$ of file m, which is the nearest one. Then, the second nearest segment (i.e., $X_{m,3}$) is delivered to

the requesting node. This continues until the requesting node receives all K distinct segments of the desired file.
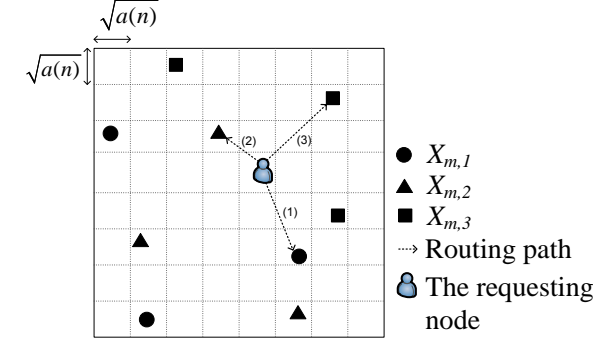
(a) Sequential reception


(b) Random reception

Figure 1: Multi-segment reception strategies for file m.
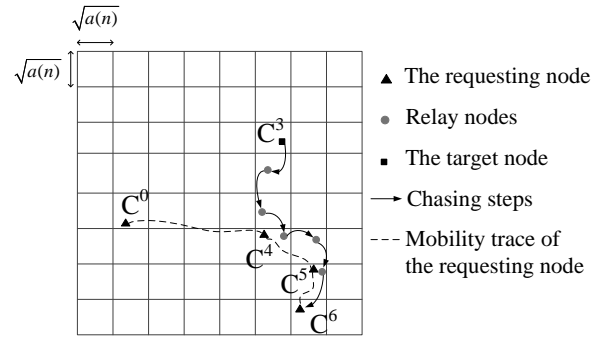
B. Segment Delivery Routing Protocol

In this subsection, we introduce the segment delivery multihop routing protocol used in our network model. For multihop transmission, the network of unit area is divided into $a(n)^{-1}$ square routing cells of equal size, where $a(n) = \Omega\left(\frac{\log n}{n}\right)$ and $a(n) = O(1)$, so that each routing cell has at least one node with high probability [3]. Assume that topology discovery and data reachability have already been accomplished in the network, so that each node knows to whom it can forward a requesting message in order to reach the desired segment holder. We implement a multihop routing strategy for segment delivery based on routing cells whose size is $a(n)$. Each routing cell is activated regularly once every $1 + c$ time slots to avoid any collision, where $c > 0$ denotes a small integer independent of n.

As illustrated in Figure 2, we apply the routing protocol in [11], which operates based on the network topology, i.e., the initial distance between a requesting node and its closest holder. When the requesting node is located inside the transmission range of any node, which is holding the requested segment, it will be served within one time slot. Otherwise, the requesting node needs to find its closest holder (in the Euclidean distance) of the desired segment. A requesting message is delivered to the closest holder along the adjacent routing cells via multihop in forward direction. Then, the desired segment chases the requesting node, which moves according to the RWMM via multihop in backward direction.
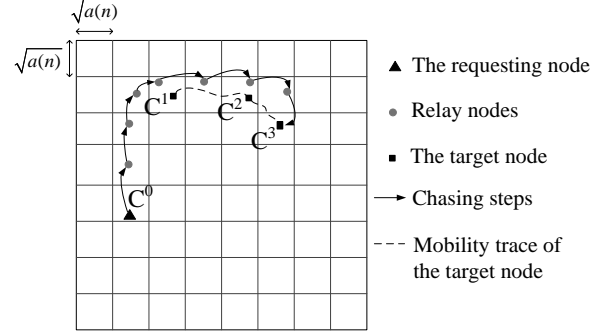
(a) The first phase

(b) The second phase

Figure 2: The segment delivery routing protocol.

IV. THROUGHPUT ANALYSIS

Similarly to [10][11], we establish the following lemma, which characterizes the throughput performance.

Lemma 1: For any mobile node requesting segment i of file $m \in \{1, \dots, M\}$, the average initial distance between any requesting node and its closest holder of segment i of file m is $\Theta\left(\frac{1}{\sqrt{X_{m,i}}}\right)$, where $X_{m,i}$ is the number of replicas of i of file m stored at nodes.

Now, let us turn to analyzing the throughput of cache-enabled mobile networks according to the two reception strategies.

1) Sequential reception

In this case, all K segments of a file are delivered in sequence. From Lemma 1, using the segment delivery routing protocol shown in the previous section, one can see that there is no need to cache more than $a(n)^{-1}$ replicas of any segment over the network. Thus, using the fact that $X_{m,i} = X_m$ for all $i \in \{1, \dots, K\}$ and $m \in \{1, \dots, M\}$, we impose the following individual caching constraints:

$$\begin{cases} X_m \le a(n)^{-1}, \\ \quad X_m \ge 1 \end{cases} \qquad (2)$$

We are ready to show the first theorem, which shows the throughput performance in our cache-enabled model using the sequential reception strategy.

Theorem 1: In a content-centric mobile network where K segments of a file are delivered using sequential reception, the throughput is given by

$$\lambda(n) = \Theta\left(\frac{1}{Kn\sum_{m=1}^{M}p_m\sqrt{\frac{a(n)}{X_m}}}\right)$$

Proof: From Lemma 1, it is shown that the aggregate distance that all segments travel to reach the requesting node is $\Theta\left(\frac{K}{\sqrt{X_{m,i}}}\right)$. Applying arguments similar to that used in [10], as the number of mobile users n goes to infinity, the number of routing lines passing through an arbitrary cell in each time slot is

$$\Theta\left(Kn\sum_{m=1}^{M}p_m\sqrt{\frac{a(n)}{X_m}}\right) whp.$$

At each time slot, each of these lines generate files passing through the routing cell. In addition, under the protocol model, there exists an interference-free schedule such that each cell gets to transmit files every $1+c$ time slots, or equivalently, the cell throughput is $\Theta(1)$. The total traffic through each cell is that due to all the routing lines and passing through each cell in (6). Accordingly, the average throughput per-node is

$$\lambda(n) = \Theta\left(\frac{1}{Kn\sum_{m=1}^{M}p_m\sqrt{\frac{a(n)}{X_m}}}\right) whp,$$

which completes the proof of the theorem.

Note that assuming $X_m = a(n)^{-1}$ for $\forall m \in \{1,...,M\}$ leads to $\lambda(n) = \Theta\left(\frac{1}{Kna(n)}\right)$, which corresponds to the maximum throughput we can hope for. Using (1), (2), and Theorem 1, we formulate the following optimization problem

Problem 1: Sequential reception case

$$\min_{\{X_m\}_{m\in\mathcal{M}}} \sum_{m=1}^{M}\frac{p_m K}{\sqrt{X_m}} \tag{4}$$

subject to:
$$\sum_{m=1}^{M} X_m \le n\frac{S}{K}$$
$$1 \le X_m \le a(n)^{-1} \text{ với } \forall m \in \mathcal{M}.$$

It is shown that, Problem 1 is solved in [10]. Then, we have:

$$X_m = \begin{cases} \dfrac{n}{\log n} & \text{for } m = 1,...,m_1-1 \\ \dfrac{p_m^{\frac{2}{3}}}{\sum_{l=m_1}^{m_2}p_l^{\frac{2}{3}}}n & \text{for } m = m_1,...,m_2-1 \\ 1 & \text{for } m = m_2,...,M \end{cases}$$

where

$$m_1 = \begin{cases} \Theta(\log n) & \text{for } \alpha > \frac{3}{2} \\ \Theta(1) & \text{for } \alpha \le \frac{3}{2} \end{cases} \quad \text{and}$$

$$m_1 = \begin{cases} \Theta\left(\min\left(M, n^{\frac{3}{2\alpha}}(\log n)^{1-\frac{3}{2\alpha}}\right)\right) & \text{for } \alpha > \frac{3}{2} \\ M & \text{for } \alpha \le \frac{3}{2} \end{cases}. \text{ We}$$

obtain,

- $\alpha > \frac{3}{2}$: $\lambda(n) = \Theta\left(\frac{1}{K\log n}\right)$;
- $\alpha = \frac{3}{2}$: $\lambda(n) = \Theta\left(\frac{1}{K(\log n)^2}\right)$;
- $1 < \alpha < \frac{3}{2}$: $\lambda(n) = \Theta\left(\frac{M^{\alpha-\frac{3}{2}}}{K\sqrt{\log n}}\right)$;
- $\alpha = 1$: $\lambda(n) = \Theta\left(\frac{\sqrt{\log n}}{K\sqrt{M}}\right)$;
- $\alpha < 1$: $\lambda(n) = \Theta\left(\frac{1}{K\sqrt{M\log n}}\right)$;

2) Random reception

In this case, a requesting node receives K segments of its desired file in an arbitrary way. For file $m \in \{1,...,M\}$, there are KX_m segments over the network. From Lemma 1, for the first segment of file m, the average distance between the requesting node and the closest holder is $\Theta\left(\frac{1}{\sqrt{KX_m}}\right)$. Since the number of the remaining segments is $(K-1)X_m$, the average distance between the requesting node and the closest holder is $\Theta\left(\frac{1}{\sqrt{(K-1)X_m}}\right)$.

Let us first consider the case where $KX_m \ge a(n)^{-1}$. The number of the remaining segments over the network is $(K-l_m+1)X_m$, for the l_m-th segment, where l_m denote the smallest index of the segment such that $(K-l_m+1)X_m \ge a(n)^{-1}$. Using Lemma 1, the aggregate distance to collect all of K segments of file m is given by $\Theta(\sqrt{a(n)}l_m)+\sum_{j=l_m-1}^{K-1}\Theta\left(\frac{1}{\sqrt{(K-j)X_m}}\right)$. Here, it follows that $\sum_{j=l_m-1}^{K-1}\Theta\left(\frac{1}{\sqrt{(K-j)X_m}}\right) = \Theta\left(\frac{\sqrt{K-l_m+1}}{\sqrt{X_m}}\right)$ due to the property of the Riemann zeta function. From the definition of l_m, we thus have $(K-l_m+1)X_m = a(n)^{-1}$. Then, the aggregate distance is $\Theta(\sqrt{a(n)}l_m) + \Theta(\sqrt{a(n)}(K-l_m+1)) = \Theta(\sqrt{a(n)}K)$, which corresponds to the minimum bound on the distance. Since there is no need to cache more than $X_m = \frac{a(n)^{-1}}{K}$ replicas of file m at nodes for all $m \in \{1,...,M\}$, we impose the following individual caching constraints

$$1 \le X_m \le \frac{a(n)^{-1}}{K} \tag{3}$$

We now establish our second theorem, which shows the throughput performance for the random reception case.

Theorem 2: In a content-centric mobile network where K segments of a file are delivered using sequential reception, the throughput is given by

$$\lambda(n) = \Theta\left(\frac{1}{n\sum_{m=1}^{M}p_m\sqrt{\frac{Ka(n)}{X_m}}}\right)$$

Proof: From Lemma 1, it is shown that the aggregate distance that all segments travel to reach the requesting node is $\sum_{j=1}^{K-1}\Theta\left(\frac{1}{\sqrt{(K-j)X_m}}\right) = \sum_{j=1}^{K-1}\frac{1}{\sqrt{K-j}}\Theta\left(\frac{1}{\sqrt{X_m}}\right) = \Theta\left(\frac{\sqrt{K}}{\sqrt{X_m}}\right)$. Similar to the proof of Theorem 1, the average throughput per-node is

$$\lambda(n) = \Theta\left(\frac{1}{n\sum_{m=1}^{M} p_m \sqrt{\frac{Ka(n)}{X_m}}}\right) whp, \qquad (4)$$

which completes the proof of the theorem.

Note that assuming $X_m = a(n)^{-1}$ for $\forall m \in \{1, \ldots, M\}$ leads to $\lambda(n) = \Theta\left(\frac{1}{\sqrt{K} na(n)}\right)$, which corresponds to the maximum throughput we can hope for.

From the fact that the total cache storage of the network is nS, if $M = O(Sna(n)) = O(S \log n)$, then the minimum aggregate distance is always achieved by the replication strategy $X_m = \frac{a(n)^{-1}}{K}$ for all m. Otherwise, using (1), (3), and Theorem 2, we formulate the second optimization problem.

Problem 2: Random reception case

$$\min_{\{X_m\}_{m \in \mathcal{M}}} \sum_{m=1}^{M} p_m \sqrt{\frac{K}{X_m}} \qquad (5)$$

subject to: $\quad \sum_{m=1}^{M} X_m \le n\frac{S}{K}$

$$1 \le X_m \le \frac{a(n)^{-1}}{K} \text{ với } \forall m \in \mathcal{M}$$

Since the objective function is convex, we are able to use the Lagrangian relaxation method for solving the problem. We now first show that the optimal solution X_m^* is non-increasing with $m \in \mathcal{M}$. The Lagrangian function corresponding to (5) is given by:

$$\mathcal{L}(X_m, \lambda, \mu_m) = \sum_{m=1}^{M} \frac{p_m}{\sqrt{X_m}} + \lambda\left(\sum_{m=1}^{M} X_m - n\frac{S}{K}\right) + \sum_{m=1}^{M} \mu_m \left(X_m - \frac{a(n)^{-1}}{K}\right), \quad (6)$$

Với λ, $\mu_m \in \mathbb{R}$. Karush-Kuhn-Tucker (KKT) conditions are then given by:

$$\begin{cases} \frac{\nabla\mathcal{L}}{\nabla X_m^*} = 0 & (7) \\ \lambda^* \ge 0 & (8) \\ \mu_m^* \ge 0 & (9) \\ \mu_m^*\left(X_m^* - \frac{a(n)^{-1}}{K}\right) = 0 & (10) \\ \lambda^*\left(\sum_{m=1}^{M} X_m^* - n\frac{S}{K}\right) = 0 & (11) \end{cases}$$

For all $\forall m \in \mathcal{M}$. From (7), we have:

$$-\frac{p_m}{2\sqrt{X_m^{*3}}} + \lambda^* + \mu_m^* = 0 \quad (12)$$

For $M = \omega(S \log n)$, there exists at least one file $m \in \mathcal{M}$ such that $X_m^* < \frac{a(n)^{-1}}{K}$. Then, we have $\mu_m^* = 0$ from (10), this leads to $\lambda^* > 0$ in (12). Using (11) we have $\sum_{m=1}^{M} X_m^* = n\frac{S}{K}$.

Let D denote the set of files such that $X_m^* = \frac{a(n)^{-1}}{K}$. Now, consider any file $m \in \mathcal{M}\backslash D$. Using (10) and (12), we have:

$$X_m^* = \frac{p_m^{\frac{2}{3}}}{(2\lambda^*)^{\frac{2}{3}}} \qquad (13)$$

Here, X_m^* decreases when m increases.

We consider $k \in D$ and $m_0 \in \mathcal{M}\backslash D$ denotes the smallest value such that $X_{m_0}^* < \frac{a(n)^{-1}}{K}$. Using (8), (9), (12), we obtain $k < m_0$. Thus, the optimal solution X_m^* is non-increasing with $m \in \mathcal{M}$.

Using (13) for all $m \in \mathcal{M}\backslash D$, we have:

$$X_m^* = \frac{p_m^{\frac{2}{3}}}{\sum_{l=m_0}^{M} p_l^{\frac{2}{3}}} \sum_{l=m_0}^{M} X_l^* \qquad (14)$$

If $X_M^* = \frac{a(n)^{-1}}{K}$, we have $\sum_{l=1}^{M} X_l^* = \frac{Ma(n)^{-1}}{K}$, this contradicts to $\sum_{m=1}^{M} X_m^* = n\frac{S}{K}$. Then, we have $X_M^* < \frac{a(n)^{-1}}{K}$. From the definition of m_0, we have $X_{m_0}^* = \Theta\left(\frac{a(n)^{-1}}{K}\right)$. Then, we have $M = o(m_0)$. From (14) we obtain:

$$\sum_{m=1}^{M} \frac{p_m}{\sqrt{X_m^*}} = \sum_{m=1}^{m_0} \frac{p_m}{\sqrt{\frac{a(n)^{-1}}{K}}} + \frac{\left(\sum_{m=m_0}^{M} p_l^{\frac{2}{3}}\right)^{\frac{3}{2}}}{\sqrt{\sum_{l=m_0}^{M} X_l^*}} \qquad (15)$$

We consider the following cases:

- $\alpha \ge \frac{3}{2}$

Applying $X_{m_0}^* = \Theta\left(\frac{a(n)^{-1}}{K}\right)$ in (14) we have:

$$\Theta\left(\frac{a(n)^{-1}}{K}\right) = \frac{p_m^{\frac{2}{3}}}{\sum_{l=m_0}^{M} p_l^{\frac{2}{3}}} \sum_{l=m_0}^{M} X_l^*$$
$$= \Theta\left(\frac{m_0^{-\frac{2\alpha}{3}}}{m_0^{1-\frac{2\alpha}{3}}} \sum_{l=m_0}^{M} X_l^*\right)$$
$$= \Theta\left(\frac{\sum_{l=m_0}^{M} X_l^*}{m_0}\right)$$

Then, The second term of (15) can be calculated as

$$\frac{\left(\sum_{m=m_0}^{M} p_l^{\frac{2}{3}}\right)^{\frac{3}{2}}}{\sqrt{\sum_{l=m_0}^{M} X_l^*}} = \Theta\left(\frac{m_0^{\frac{3}{2}-\alpha}}{\sqrt{\frac{a(n)^{-1}}{K} m_0}}\right) = \Theta\left(\frac{m_0^{1-\alpha}}{\sqrt{\frac{a(n)^{-1}}{K}}}\right)$$. Since $m_0 \ge 1$, we have $\sum_{m=1}^{M} \frac{p_m}{\sqrt{X_m^*}}$ scales as the first term of (15) is $\sqrt{\frac{K}{a(n)^{-1}}}$. We have $\lambda(n) = \Theta(\frac{1}{K \log n})$ where $a(n) = \Theta\left(\frac{\log n}{n}\right)$.

- $\frac{3}{2} > \alpha > 1$

From (15) we have

$$\sum_{m=1}^{M} \frac{p_m}{\sqrt{X_m^*}} = \Theta\left(\sqrt{\frac{K}{a(n)^{-1}}}\right) + \Theta\left(\frac{M^{\frac{3}{2}-\alpha}}{\sqrt{\sum_{l=m_0}^{M} X_l^*}}\right)$$

Then,

- $\frac{3}{2} > \alpha \ge \frac{3}{2} - \frac{\beta}{2\gamma}$: We always have $\sum_{m=1}^{M} \frac{p_m}{\sqrt{X_m^*}} = \Theta\left(\sqrt{\frac{K}{a(n)^{-1}}}\right)$, which is the best

that we can hope for. Then, $\lambda(n) = \Theta(\frac{1}{K \log n})$ where $a(n) = \Theta\left(\frac{\log n}{n}\right)$.

○ $\frac{3}{2} - \frac{\beta}{2\gamma} > \alpha > 1$: The second term is dominant, we have $\sum_{m=1}^{M} \frac{p_m}{\sqrt{X_m^*}} = \Theta\left(\frac{M^{\frac{3}{2} - \alpha}}{\sqrt{n}}\right)$ where $a(n) = \Theta\left(\frac{\log n}{n}\right)$. Then $\lambda(n) = \Theta\left(\frac{M^{\alpha - \frac{3}{2}}}{\sqrt{K \log n}}\right)$;

- $\alpha = 1$: Similarly, we have $\sum_{m=1}^{M} \frac{p_m}{\sqrt{X_m^*}} = \Theta\left(\frac{\sqrt{M}}{\sqrt{n \log n}}\right)$ where $a(n) = \Theta\left(\frac{\log n}{n}\right)$. Then $\lambda(n) = \Theta\left(\frac{\sqrt{\log n}}{\sqrt{KM}}\right)$.

- $\alpha < 1$: Similarly, we have $\sum_{m=1}^{M} \frac{p_m}{\sqrt{X_m^*}} = \Theta\left(\frac{\sqrt{M}}{\sqrt{n}}\right)$ where $a(n) = \Theta\left(\frac{\log n}{n}\right)$. Then, $\lambda(n) = \Theta\left(\frac{1}{\sqrt{KM \log n}}\right)$.
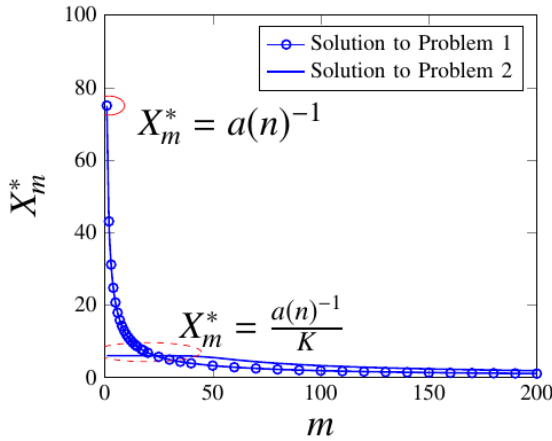

Figure 3: The optimal sets X_m^* of Problem 1 and Problem 2 with respect to the file m.

As depicted in Fig. 3, the results show that X_m^* basically decreases as m increases for Problem 1; for Problem 2, X_m^* is fixed to a certain value for small m and then decreases as m increases. The difference comes from the individual caching constraints imposed in two reception strategies in (2) and (3). From the analytical results, it is shown that using random reception yields better performance on the throughput than the sequential reception case. This is because random reception tends to operate more flexibly in the sense of collecting K segments as there is no a priori reception order of the segments, thus leading to the improvement of throughput.

V. CONCLUSIONS

In this paper, we studied the throughput of a content-centric mobile ad hoc network, where each file is divided into K distinct segments of equal size such that each of n mobile nodes is able to completely transmit one segment to one of its neighbor cells in one time slot. By introducing the sequential and random reception strategies, we analyzed the throughput scaling law and then found the optimal cache allocation strategies in terms of maximizing the throughput. As our main result, it was shown that the random reception strategy outperforms the sequential reception one.

REFERENCES

[1] V. Jacobson, D. K. Smetters, J. D. Thornton, M. F. Plass, N. H. Briggs, and R. L. Braynard, "*Networking named content,*" Commun. ACM, vol. 55, no. 1, pp. 117–124, Jan. 2012.

[2] "*Cisco visual networking index: Global mobile data traffic forecast update, 2015-2020,*" Cisco Public Information, Feb. 2016.

[3] P. Gupta and P. R. Kumar, "*The capacity of wireless networks,*" IEEE Trans. Inf. Theory, vol. 46, no. 2, pp. 388–404, Mar. 2000.

[4] A. Özgür, O. Lévêque, and D. N. C. Tse, "*Hierarchical cooperation achieves optimal capacity scaling in ad hoc networks,*" IEEE Trans. Inf. Theory, vol. 53, no. 10, pp. 3549–3572, Oct. 2007.

[5] M. Grossglauser and D. N. C. Tse, "*Mobility increases the capacity of ad hoc wireless networks,*" IEEE/ACM Trans. Netw., vol. 10, no. 4, pp. 477–486, Aug. 2002.

[6] A. El Gamal, J. Mammen, B. Prabhakar, and D. Shah, "*Optimal throughput–delay scaling in wireless networks–Part I: The fluid model,*" IEEE Trans. Inf. Theory, vol. 52, no. 6, pp. 2568–2592, Jun. 2006.

[7] S. Gitzenis, G. S. Paschos, and L. Tassiulas, "*Asymptotic laws for joint content replication and delivery in wireless networks,*" IEEE Trans. Inf. Theory, vol. 59, no. 5, pp. 2760–2776, May 2013.

[8] S.-W. Jeon, S.-N. Hong, M. Ji, G. Caire, and A. F. Molisch, "*Wireless multihop device-to-device caching networks,*" IEEE Trans. Inf. Theory, vol. 63, no. 3, pp. 1662–1676, Mar. 2017.

[9] G. Alfano, M. Garetto, and E. Leonardi, "*Content-centric wireless networks with limited buffers: When mobility hurts,*" IEEE/ACM Trans. Netw., vol. 24, no. 1, pp. 299–311, Feb. 2016.

[10] M. Mahdian and E. Yeh, "*Throughput–delay Scaling of content-centric ad hoc and heterogeneous wireless networks,*" IEEE/ACM Trans. Netw., vol. 25, no. 5, pp. 3030–3043, Oct. 2017.

[11] T.-A. Do, S.-W. Jeon, and W.-Y. Shin, "*Caching in mobile HetNets: A throughput-delay trade-off perspective,*" in Proc. IEEE Int. Symp. Inf. Theory (ISIT), Barcelona, Spain, Jul. 2016, pp. 1247-1251.

[12] M. Ji, G. Caire, and A. F. Molisch, "*Fundamental limits of caching in wireless D2D networks,*" IEEE Trans. Inf. Theory, vol. 62, no. 2, pp. 849–869, Feb. 2016.

[13] V. Bioglio, F. Gabry, and I. Land, "*Optimizing MDS codes for caching at the edge,*" in Proc. IEEE Global Telecommun. (GLOBECOM), San Diego, CA, Dec. 2015, pp. 1–6.

[14] D. E. Knuth, "*Big Omicron and big Omega and big Theta,*" ACM SIGACT News, vol. 8, no. 2, pp. 18–24, Apr.–Jun. 1976.

TỐI ƯU HÓA ĐỆM DỮ LIỆU TRONG MẠNG DI ĐỘNG HƯỚNG NỘI DUNG SỬ DỤNG PHƯƠNG PHÁP PHÂN MẢNH TỆP TIN

Tóm tắt: Trong bài báo này, chúng tôi nghiên cứu tối ưu hóa đệm dữ liệu trong mạng ad hoc di động hướng nội dung để đạt được mức thông lượng tốt nhất với các nốt mạng di chuyển sử dụng giao thức multihop theo mô hình bước ngẫu nhiên (random walk mobility). Trong đó, mỗi nốt mạng yêu cầu tải một tệp tin từ thư viện chung của mạng một cách độc lập và ngẫu nhiên, tuân theo phân bố Zipf. Mỗi tệp tin được cấu thành bởi K mảnh tin khác nhau và có kích thước bằng nhau sao cho mỗi nốt mạng có thể hoàn tất quá trình truyền một mảnh tin tới nốt mạng lân cận bất kỳ ở mỗi khe thời

gian. Sử dụng giao thức truyền dẫn multihop, giá trị biến thiên của thông lượng sẽ được phân tích dựa trên hai phương pháp thu nhận mảnh tin tuần tự và ngẫu nhiên. Trong bài báo này, chúng tôi xây dựng và giải bài toán tối ưu tương ứng tìm ra phương pháp đệm dữ liệu tối ưu sao cho đạt được mức thông lượng lớn nhất. Kết quả thu được cho thấy thông lượng tối ưu trong mô hình mạng sử dụng phương pháp thu nhận mảnh tin ngẫu nhiên tốt hơn đáng kể so với thông lượng tối ưu trong mô hình mạng sử dụng phương pháp thu nhận mảnh tin tuần tự.

Trung-Anh Do received the B.S. and the M.S. degrees in Telecommunications and Electronics Engineering from Hanoi University of Technoloty, Hanoi, Vietnam, in 2009 and 2011, respectively. From 2011 to 2014, he was a researcher in Research Institute of Posts and Telecommunications, Hanoi, Vietnam. From 2014 to 2016, he was a researcher in Communications and Networking Laboratory at Dankook University, Yongin, Korea. He is now pursuing a Ph.D degree in Telecommunications Engineering at Posts and Telecommunications Institute of Technology, Hanoi, Vietnam. His research interests include wireless communications and big data analytics.

Ngoc Chu Quang received the B.E. degree from the Hanoi University of Technology,Hanoi, Vietnam, in 1996, and the M.E. degree from Computer Science Íntitute for the Francophonie, Hanoi, Vietnam in 1998, both in information technology; He is currently an Researcher/Director at Posts and Telecommunications Training Center number I - PTIT. His current research interests include big data analytics and applying machine learning in wireless communication.

Bac Dang Hoai received the B.E. degree from the Hanoi University of Technology,Hanoi, Vietnam, in 1997, and both the M.E. degree and the Ph.D. degree from the Posts and Telecommunications Institute of Technology (PTIT), Hanoi, Vietnam in 2004 and 2010, respectively, both in electronics and telecommunications. He is currently an Associate Professor/Vice Director at PTIT. His current research interests include the area of communication theory with a particular emphasis on modeling, design, and performance evaluation.