Optimal Content Transmission Policy in Publish-Subscribe Mobile Social Networks

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***Abstract*—We consider the problem of dynamic content distribution in publish-subscribe mobile social networks. Mobile users subscribe to the content provider. Then, when new content is created, the provider transmits it to subscribers (i.e., mobile users) through the base station. The mobile users who have the social relationship (i.e., mobile users in the same community) can transfer the fresh content when they move and meet each other. From the content provider's perspective, the content transmission policy by the base station can be optimized so that the number of mobile users having the fresh data is maximized subject to the constraint on the maximum waiting time of the new content. An optimization formulation is presented for the content provider to obtain this optimal content transmission policy. Performance evaluation results show that with the optimal content transmission policy, the average number of mobile users having fresh content is larger than that if the new content is transmitted immediately.**

Keywords: Mobile social networks, publish-subscribe model, content distribution, constrained Markov decision process (CMDP), probability of content transmission.

I. INTRODUCTION

The concept of social network has been introduced to enable people to keep in touch with friends, building communities of people who share common interest and/or activities, and facilitating communications and information sharing between them. This concept has recently been extended to mobile social network for mobile users [1]. One of the mobile social networks is based on publish-subscribe model in which the mobile users subscribe to the content provider to receive published content. Then, mobile users with fresh content can carry and forward the content to other users who have the common interest (i.e., in the same community). One challenging issue in this mobile social network is how to increase the speed of content distribution and/or to maximize the number of mobile users receiving the fresh content. From the mobile users' perspective, this objective can be achieved by improving the routing protocol, which has been studied extensively in the literature (e.g., [2], [3], [4]). However, very few works considered this issue from the content providers' perspective, i.e., how the base station of content provider transmits new content to the mobile users.

One example of the aforementioned content distribution in mobile social networks is the distribution of application updates. A base station broadcasts new application updates to the users in its coverage area. To reduce the load of the base station, the content provider allows the users to transfer new updates among each other in the same community whose members use the same application. However, if the users want to start using the new updates, they have to register to the content provider, which can be performed, for example, through short messaging services (SMS). The application update can have waiting time constraint, e.g., antivirus software which is required to ensure that the update for the new virus must be distributed by content provider to the users on time.

We address the problem of optimal content transmission from the content providers' perspective. Specifically, the base station of a content provider optimally transmits new content to the mobile nodes (i.e., mobile users) so that the number of nodes having the fresh content is maximized. In addition, the base station has to ensure that the waiting time of the content before being released to the user is maintained below a threshold value. To achieve this objective, we develop an optimization model based on constrained Markov decision process (CMDP). The parameters of this CMDP model are the average duration of mobile nodes to be inside and outside the coverage area of base station, and the average inter-encounter interval. The solution of this optimization formulation determines the action of base station (i.e., whether to transmit new content or not) given the state of the network (e.g., the number of mobile users in the coverage area and the number of contents waiting in queue of base station). The numerical studies show that if the base station holds the new content in queue and releases it properly, the number of mobile users having the fresh content will be much larger than that if base station transmits the new content immediately. The optimization model developed in this paper will be useful for the design and analysis of dynamic content distribution schemes in mobile social networks.

II. RELATED WORK

In [2], architecture of a mobile ad hoc transient network was proposed to provide content delivery for a community of users. Here an intelligent agent utilizes the social relationship among the users in the same community to cooperatively retrieve and share remote content. The social relationship was proved to enhance the performance of routing protocol in delay tolerant networks [3] which is the basis of mobile social networks [4]. In [5], a content delivery scheme based on opportunistic spatial gossip was proposed for mobile social networks. In this scheme, a network node selects not only the forwarder, but also the message to be forwarded according to the past relationship. In [6], a routing scheme, namely, SocialCast was proposed for publish-subscribe mobile social networks.

In [7], a content delivery scheme was proposed for mobile social networks. This scheme performs the selection of carrier by taking not only the mobility pattern, but also the meeting time of the people into account. As a result, the content delivery can be optimized for time-critical applications by reducing the end-to-end delay significantly. In [8], a community-based data transmission scheme was proposed to limit the content distribution and hence reduce the overhead in mobile social networks. This scheme divides mobile users into different communities based on the contact frequency. The number of content copies to be distributed to the users in the different communities is adjusted adaptively. In [9], an optimal bandwidth allocation scheme was developed to transmit content from content provider to users. The objective is to maximize the utility of all users in which the utility is defined as a decreasing function of content age. That is, the older the data obtained by the user, the smaller the utility is. However, in all the above and other related work, the problem of data transmission by the publisher (i.e., base station or access point) to the users was ignored.

III. System Model and Assumptions

We consider a publish-subscribe mobile social network model for dynamic content distribution service similar to that in [9]. The components of this model are as follows:

- Content provider distributes the content (e.g., application update) to the mobile users through the base station.
- The base station is the communication point to broadcast the new content from content provider to the mobile users.
- N mobile nodes subscribe to receive content broadcast from the base station.

Once a new content is created by provider, it is stored in the queue of the base station with maximum capacity of B contents (i.e., files). Then, the base station releases the new content to the nodes in its coverage area. We assume that the new content is broadcast to the users in the coverage area of the base station. The mobile nodes with the latest content from the base station (i.e., fresh content[1]) can move and meet other nodes in the same community. The fresh content will be transferred among the meeting nodes if the fresh content is newer than that in other nodes. In this way, the fresh contents can be transmitted to the mobile nodes even though they are not in the coverage area of the base station.

We assume that all mobile nodes in the same community are interested in the content transmitted by the content provider. The new content is generated by content provider and sent to the base station according to a Poisson process with average rate λ_{BS} per minute. The average transmission time of the content from the base station to mobile nodes is $1/\mu$. As the mobile nodes move, the inter-encounter interval is defined as the time interval between two consecutive meetings of two nodes. This inter-encounter interval is assumed to be exponentially distributed with mean $1/\lambda$ minutes [3]. From the trace data, it was shown that exponential distribution can be well fit to the inter-encounter interval of mobile users. The inter-encounter rate is λ per minute. Whenever the nodes meet, they can successfully transfer the fresh content. As the mobile nodes move, the average time interval for a node to be outside and to be inside coverage area of the base station are $1/\alpha$ and $1/\beta$ minutes, respectively.

[1] For the rest of the paper, we use the terms "the latest content from base station" and "fresh content" interchangeably. On the other hand, "new content" refers to the content generated by provider and waiting in queue of base station.

Fig. 1 shows an example of the publish-subscribe mobile social network model. Let nodes 1 to N be in the same community. First, nodes 1 and 5 are in the coverage area of the base station. There is new content stored in queue, and the base station decides to transmit this new content to nodes 1 and 5. Then, node 1 moves and meets node 2, while node 5 moves and meets node 6. The fresh content is transferred from node 1 to node 2 and from node 5 to node 6. Again, node 1 moves and meets node 3, and simultaneously node 2 moves and meets node 4. The fresh content is transferred from node 1 to node 3 and from node 2 to node 4, and so on.

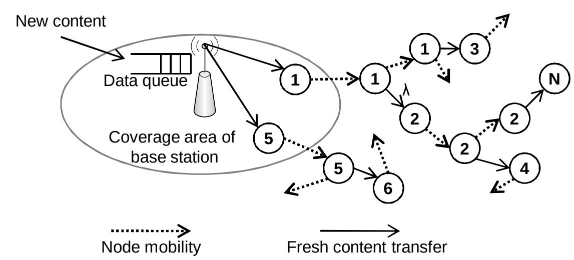

Fig. 1. Example of the publish-subscribe mobile social network model.

In this mobile social network model, the benefit of content provider is a non-decreasing function of the number of nodes receiving the content. In addition, since the nodes have to register for the content, the content provider can keep track of the current number of nodes with fresh content. In the following, an optimization formulation will be developed to maximize the number of mobile nodes having the fresh content. This objective is equivalent to maximizing the revenue from content distribution if a pay-per-copy pricing scheme is used.

IV. Optimization Formulation of Content Transmission by Publisher

In this section, an optimization formulation based on constrained Markov decision process (CMDP) is presented for the base station to transmit the content. First, the state and action spaces are defined. Then, the transition matrix is derived. The optimal policy and performance measures are obtained.

A. State and Action Spaces

The state space of content distribution for the base station (i.e., content provider) is defined as follows:

$$\Omega = \{(\mathcal{N}, \mathcal{Q}, \mathcal{C}); \mathcal{N} \in \{1, \ldots, N\}, \mathcal{Q} \in \{0, 1, \ldots, B\}, \mathcal{C} \in \{0, 1, \ldots, N\}\} \quad (1)$$

where $\mathcal{N}$ is the number of mobile nodes having fresh content from the content provider, $\mathcal{Q}$ represents the number of content files in the queue with size B, and $\mathcal{C}$ represents the number of mobile nodes in the coverage area of the base station.

The action of the base station is denoted as $a \in \mathcal{A}$, where $\mathcal{A} = \{0, 1\}$ is the action space. Action $a = 0$ corresponds to the decision of not transmitting while $a = 1$ is the decision of transmitting the new content in queue to the mobile nodes. The action is performed when the state of content distribution changes.

B. Transition Matrix

The transition matrix for the states in Ω is based on the following conditions.

- The number of content files in queue increases with rate λ_{BS}. This number decreases with rate μ if action $a = 1$, and zero otherwise.
- Let c denote the number of mobile nodes in the coverage area of the base station. This number increases with rate $\alpha(N - c)$ and decreases with rate βc.
- Let n denote the number of nodes having fresh content from the base station. This number increases with rate $n\lambda(N - n)$ if action $a = 0$. This number decreases to c with rate μ if action $a = 1$, i.e., the base station releases the new content which becomes fresh content to mobile nodes.

In the first step, we consider the state transition for the number of mobile nodes in the coverage area of base station. The transition matrix can be defined as in (2) in the next page where $\mathbf{C}_{c,c'}(a)$ represents the transition matrix for the number of mobile nodes in the coverage area changing from c to c' given action a. For $c \neq c'$, these matrices can be obtained from

$$\mathbf{C}_{c,c'}(a) = \begin{cases} \alpha(N-c)\mathbf{I}, & c' = c+1, 0 \leq c < N \\ \beta c\mathbf{I}, & c' = c-1, 0 < c \leq N \\ \mathbf{0}, & \text{otherwise} \end{cases} \quad (3)$$

where $\mathbf{I}$ is the identity matrix and $\mathbf{0}$ is a matrix of zeros. Matrices $\mathbf{C}_{c,c+1}(a)$ and $\mathbf{C}_{c,c-1}(a)$ capture the transitions of node arrival and departure from the coverage area, respectively. Matrix $\mathbf{C}_{c,c}(a)$ captures the transition of number of contents in queue at the base station and the number of mobile nodes having fresh content. This matrix is defined as in (4) in the next page where $\mathbf{Q}^{(c)}_{q,q'}(a)$ represents the transition matrix for the number of contents in queue changing from q to q' when there are c nodes in the coverage area of the base station. This matrix $\mathbf{Q}^{(c)}_{q,q'}(a)$ captures the content arrival and departure from the base station when action a is taken. For $q \neq q'$, these matrices can be obtained from

$$\mathbf{Q}_{q,q'}(a) = \begin{cases} \lambda_{\mathrm{BS}}\mathbf{I}, & q' = q+1, 0 \leq q < B \\ \mu\mathbf{I}, & q' = q-1, 0 < q \leq B, a = 1 \\ \mathbf{0}, & \text{otherwise.} \end{cases} \quad (5)$$

Matrix $\mathbf{Q}^{(c)}_{q,q}(a)$ captures the transition of the number of mobile nodes having fresh content. For $n \neq n'$, this matrix is defined as follows:

$$\mathbf{Q}^{(c)}_{q,q}(a) = \begin{bmatrix} \eta^{(c,q)}_{0,0}(a) & \cdots & \eta^{(c,q)}_{0,N}(a) \\ \vdots & & \vdots \\ \eta^{(c,q)}_{N,0}(a) & \cdots & \eta^{(c,q)}_{N,N}(a) \end{bmatrix} \quad (6)$$

where the element $\eta^{(c,q)}_{n,n'}(a)$ is the transition rate when the number of mobile nodes having fresh content changes from n to n'. This element can be obtained from

$$\eta^{(c,q)}_{n,n'}(a) = \begin{cases} n\lambda(N-n), & n' = n+1, 1 \leq n < N, a = 0 \\ \mu, & n' = c, a = 1 \\ 0, & \text{otherwise.} \end{cases} \quad (7)$$

In (7), the first condition corresponds to the case that there is no new content transmitted by the base station, and mobile nodes are willing to transfer the current fresh content. In the second condition, as the new content is transmitted, content provider can ignore the transfer of obsolete content as it does not yield any more revenue. Therefore, the number of nodes having the new fresh data (i.e., the mobile nodes receiving broadcast content from base station) equals to the number of mobile nodes c in the coverage area of the base station. The diagonal elements $\eta^{(c,q)}_{n,n}(a)$ have negative values such that the sum of elements of any row is zero. For example, for $0 < n < N$, $0 < q < B$, and $0 < c < N$, the diagonal element can be obtained from

$$\eta^{(c,q)}_{n,n}(a) = -\sum_{n' \neq n} \eta^{(c,q)}_{n,n'}(a) - \mu - \lambda_{\mathrm{BS}} - \alpha - \beta. \quad (8)$$

The transition rate matrix $\mathbf{P}(a)$ defined in (2) can be transformed into an equivalent transition probability matrix $\hat{\mathbf{P}}(a)$ by using uniformization method [10] as follows:

$$\hat{\mathbf{P}}(a) = \frac{\mathbf{P}(a)}{\nu} + \mathbf{I} \quad \text{for} \quad a \in \mathcal{A} \quad (9)$$

where $\nu \geq \min_{n,c,q,a}\left(\left|\eta^{(c,q)}_{n,n}(a)\right|\right)$ for $n = \{0, 1, \ldots, N\}$, $q = \{0, \ldots, B\}$, $c = \{0, 1, \ldots, N\}$, and $a = \{0, 1\}$. In other words, ν is greater than or equal to the absolute value of the minimum diagonal element in $\mathbf{P}(a)$.

C. Optimal Policy

The base station optimizes the content transmission policy π (i.e., whether to transmit new content waiting in queue or not). This policy π is a mapping of state $s \in \Omega$ to action $a \in \mathcal{A}$ to maximize the number of mobile nodes having fresh content while the average waiting time of content in queue is less than or equal to threshold $W_{\max}$. The CMDP model can be formulated as in (10)-(11) where $\mathscr{J}_{\mathrm{N}}(\pi)$ and $\mathscr{J}_{\mathrm{W}}(\pi)$ are the average number of mobile nodes having fresh content and the average waiting time of content in queue, respectively. ($\mathcal{N}_{t'}$, $\mathcal{Q}_{t'}$, $\mathcal{C}_{t'}$) and $\mathcal{A}_{t'}$ denote, respectively, the state and the action, respectively. $E_\pi(\cdot)$ denotes the expectation over policy π. $\mathscr{N}(n, q, c)$ and $\mathscr{W}(n, q, c)$ denote, respectively, the number of mobile nodes having fresh content and the immediate waiting time of content in the base station queue. n is the number of mobile nodes having fresh content, q is the number of contents in queue, and c is the number of mobile nodes in the coverage area of the base station. The performance measures can be obtained from

$$E\left(\mathscr{N}((n, q, c), a)\right) = E(n) \quad (12)$$

$$E\left(\mathscr{W}((n, q, c), a)\right) = E\left(q/\lambda_{\mathrm{BS}}\right). \quad (13)$$

$$\mathbf{P}(a) = \begin{bmatrix} \mathbf{C}_{0,0}(a) & \mathbf{C}_{0,1}(a) & & & \\ \mathbf{C}_{1,0}(a) & \mathbf{C}_{1,1}(a) & \mathbf{C}_{1,2}(a) & & \\ & \ddots & \ddots & \ddots & \\ & & \mathbf{C}_{N-1,N-2}(a) & \mathbf{C}_{N-1,N-1}(a) & \mathbf{C}_{N-1,N}(a) \\ & & & \mathbf{C}_{N,N-1}(a) & \mathbf{C}_{N,N}(a) \end{bmatrix} \tag{2}$$

$$\mathbf{C}_{c,c}(a) = \begin{bmatrix} \mathbf{Q}^{(c)}_{0,0}(a) & \mathbf{Q}^{(c)}_{0,1}(a) & & & \\ \mathbf{Q}^{(c)}_{1,0}(a) & \mathbf{Q}^{(c)}_{1,1}(a) & \mathbf{Q}^{(c)}_{1,2}(a) & & \\ & \ddots & \ddots & \ddots & \\ & & \mathbf{Q}^{(c)}_{B-1,B-2}(a) & \mathbf{Q}^{(c)}_{B-1,B-1}(a) & \mathbf{Q}^{(c)}_{B-1,B}(a) \\ & & & \mathbf{Q}^{(c)}_{B,B-1}(a) & \mathbf{Q}^{(c)}_{B,B}(a) \end{bmatrix} \tag{4}$$

$$\text{maximize:} \quad \mathscr{J}_{\mathrm{N}}(\pi) = \lim_{t\to\infty} \inf \frac{1}{t} \sum_{t'=1}^{t} E_\pi \left(\mathscr{N}((\mathcal{N}_{t'}, \mathcal{Q}_{t'}, \mathcal{C}_{t'}), (\mathcal{A}_{t'})) \right) \tag{10}$$

$$\text{subject to:} \quad \mathscr{J}_{\mathrm{W}}(\pi) = \lim_{t\to\infty} \sup \frac{1}{t} \sum_{t'=1}^{t} E_\pi \left(\mathscr{W}((\mathcal{N}_{t'}, \mathcal{Q}_{t'}, \mathcal{C}_{t'}), (\mathcal{A}_{t'})) \right) \leq W_{\max} \tag{11}$$

$$\text{maximize:} \quad \sum_{(n,q,c)\in\Omega} \sum_{a\in\mathcal{A}} \phi((n,q,c),a) \mathscr{N}((n,q,c),a) \tag{14}$$

$$\text{subject to:} \quad \sum_{(n,q,c)\in\Omega} \sum_{a\in\mathcal{A}} \phi((n,q,c),a) \mathscr{W}((n,q,c),a) \leq W_{\max} \tag{15}$$

$$\sum_{a\in\mathcal{A}} \phi((n,q,c)',a) = \sum_{(n,q,c)\in\Omega} \sum_{a\in\mathcal{A}} \hat{P}((n,q,c)'|(n,q,c),a)\phi((n,q,c),a) \tag{16}$$

$$\sum_{(n,q,c)\in\Omega} \sum_{a\in\mathcal{A}} \phi((n,q,c),a) = 1, \quad \phi((n,q,c),a) \geq 0. \tag{17}$$

An equivalent linear programming model for the CMDP defined in (10)-(11) is formulated. The decision variable of this equivalent linear programming model is denoted as $\phi((n,q,c),a)$, i.e., the probability of taking action a at state (n,q,c). The equivalent linear programming is expressed as in (14)-(17) in the next page for $(n,q,c)' \in \Omega$. $\hat{P}((n,q,c)'|(n,q,c),a)$ (which is an element of matrix $\hat{\mathbf{P}}(a)$ defined in (9)) is the probability that the state changes from (n,q,c) to $(n,q,c)'$ when action a is taken.

Given the optimal solution $\phi^*((n,q,c),a)$ of the linear program defined in (14)-(17), the optimal randomized policy π^* can be obtained as follows:

$$\psi_{\pi^*}((n,q,c),a) = \frac{\phi^*((n,q,c),a)}{\sum_{a'\in\mathcal{A}} \phi^*((n,q,c),a')} \tag{18}$$

for $\sum_{a'\in\mathcal{A}} \phi^*((n,q,c),a') > 0$, where $\psi_{\pi^*}((n,q,c),a)$ is the probability that action a is taken given state (n,q,c).

D. Performance Measures

The performance measures for the base station can be obtained from the stationary state probability given the optimal policy π^*. When optimal policy π^* is applied, the stationary state probability is denoted by $p_{\pi^*}(n,q,c)$ for state $(n,q,c) \in \Omega$. Let $\vec{\mathbf{p}}_{\pi^*} = \left[\begin{array}{ccccc} p_{\pi^*}(0,0,0) & \cdots & p_{\pi^*}(n,q,c) & \cdots & p_{\pi^*}(N,B,N) \end{array} \right]^T$ denote the stationary state probability vector which can be obtained by solving the following set of equations: $\vec{\mathbf{p}}_{\pi^*}^T \hat{\mathbf{P}}_{\pi^*} = \vec{\mathbf{p}}_{\pi^*}^T$ and $\vec{\mathbf{p}}_{\pi^*}^T \vec{\mathbf{1}} = 1$, where $\vec{\mathbf{1}}$ is a vector of ones and $\hat{\mathbf{P}}_{\pi^*}$ is the transition probability matrix when the optimal randomized policy π^* is applied for content transmission of the base station.

The average number of mobile nodes having fresh data can be obtained from

$$\overline{n}_{\pi^*} = \sum_{n=0}^{N} n \left(\sum_{q=0}^{B} \sum_{c=0}^{N} p_{\pi^*}(n,q,c) \right). \tag{19}$$

The average waiting time for the content in queue of base station is calculated from

$$\overline{W}_{\pi^*} = \frac{\overline{q}_{\pi^*}}{\lambda_{\mathrm{BS}}} \tag{20}$$

where $\overline{q}_{\pi^*}$ is the average number of contents in queue, which is obtained from

$$\overline{q}_{\pi^*} = \sum_{q=0}^{B} q \left(\sum_{n=0}^{N} \sum_{c=0}^{N} p_{\pi^*}(n,q,c) \right). \tag{21}$$

V. Performance Evaluation

A. Parameter Setting

We consider a service provider providing content distribution to a community of mobile nodes. Unless stated otherwise, the number of mobile nodes in the community is $N = 50$. The average inter-encounter interval is $1/\lambda = 100$ minutes. 10 contents are generated per hour. The average durations of mobile nodes to be outside and to be inside the coverage area of base station are $1/\alpha = 50$ minutes and $1/\beta = 100$ minutes, respectively. The maximum waiting time of content in queue is $W_{\max} = 10$ minutes. The capacity of the queue is $B = 5$ files. We also consider the immediate transmission scheme where the base station transmits new content immediately.

B. Numerical Results

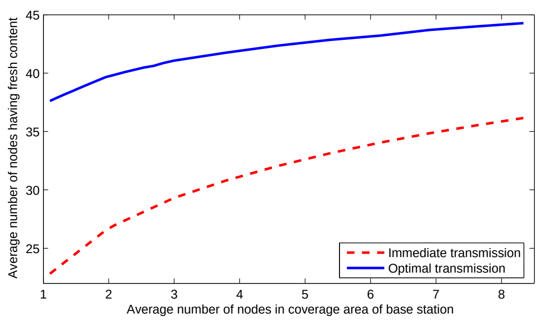

Fig. 2. Number of nodes having the fresh content from the base station under varied average number of nodes in the coverage area of the base station.

Fig. 2 shows the average number of nodes having fresh content. Under different mobility setting (e.g., mobile nodes stay in the coverage area of the base station longer), the average number of nodes in the coverage area of the base station can vary. As the average number of nodes in the coverage area of the base station increases, the new content transmission by the base station will be received by multiple nodes. Consequently, the multiple copies of content will be forwarded to other nodes faster. It can be observed that with the optimal content transmission policy the number of nodes having fresh content is much larger than that for immediate transmission.

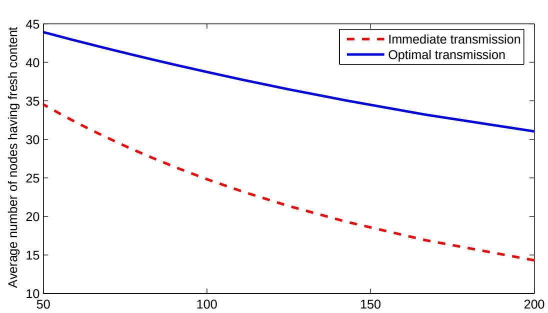

Fig. 3. Number of nodes having fresh content under varied average inter-encounter time interval.

A similar effect is observed in Fig. 3. When the average inter-encounter time interval is small, the nodes meet each other more frequently and the fresh content can be forwarded among them faster. As a result, the number of nodes having fresh content increases as the average inter-encounter interval decreases. Again, the average number of nodes having fresh content is much larger for optimal transmission when compared to that for immediate transmission.

VI. Summary

In this paper, we have addressed the question of when the base station should transmit (i.e., publish) the new content to the subscribing mobile users. This transmission should be performed so that the number of nodes having fresh content is maximized while the new content does not wait too long at the base station. An optimization formulation based on constrained Markov decision process has been developed to obtain optimal transmission policy. This optimal content transmission policy for the base station can increase the number of nodes having fresh content in a mobile social network by holding the new content in the queue and allowing the mobile nodes to forward the content for a longer period of time. By taking the state of the network into account, the content transmission policy can be optimized given the content waiting time constraint.

For the future work, competition among multiple content providers will be considered. Also, the heterogeneity of mobile users (e.g., different groups of users with different inter-encounter rate) will be modeled.

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