PAPER

Nonlinear Integer Programming Formulation for Quasi-Optimal Grouping of Clusters in Ferry-Assisted DTNs*

Masahiro SASABE[†a)], *Member*, **K. Habibul KABIR**[†b)], *Nonmember*, *and* **Tetsuya TAKINE**[†c)], *Member*

SUMMARY Communication among isolated networks (clusters) in delay tolerant networks (DTNs) can be supported by a message ferry, which collects bundles from clusters and delivers them to a sink node. When there are lots of distant static clusters, multiple message ferries and sink nodes will be required. In this paper, we aim to make groups, each of which consists of physically close clusters, a sink node, and a message ferry. Our main objective is minimizing the overall mean delivery delay of bundles in consideration of both the offered load of clusters and distances between clusters and their sink nodes. We first model this problem as a nonlinear integer programming, utilizing the existing result. Using a commercial nonlinear solver, we obtain the quasi-optimal grouping. Through numerical evaluations, we show the fundamental characteristics of grouping, the impact of location limitation of base clusters, and the tradeoff between delivery delay and introduction costs.

key words: *ferry-assisted DTN, grouping clusters, integer programming formulation.*

1. Introduction

The current end-to-end TCP/IP model does not adequately match with delay tolerant networks (DTNs) [1, 2], where there are no permanent end-to-end connections. Alternatively, a store-carry-forward message delivery scheme [1] and custody transfer mechanism [3] are used in those networks to assure reliable bundle transfers among nodes, where a bundle is the protocol data unit in DTNs. They perform a hop-by-hop reliable bundle transfer from a source node to its destination. To provide the opportunity of communication among isolated networks called *clusters*, message ferry schemes can be used [13,14], where a special mobile node proactively visits each cluster. This kind of networks are applicable to sensor networking among physically distant regions and communications among rural areas without network infrastructure, e.g., DakNet [9]. In such situations, the system periodically collects information from isolated multi-cluster DTNs, where nodes can only communicate directly/indirectly with each other within a cluster through multi-hop communication. It is usually assumed that there exists a fixed base station called *sink node*, which serves as a connector to the Internet or to other sink nodes. In such a scenario, a message ferry helps the inter-cluster communication by acting as a mediator between each cluster and the outer world via the sink node. We call this scenario ferry-assisted multi-cluster DTNs.

In actual situations, the arrival rates of bundles at clusters are different from each other. For example, the clusters can be regarded as village, town, or city, in the rural-area communications. If the arrival rates of bundles at clusters are different from each other and service times are not negligible, the conventional traveling salesman problem (TSP) solution does not work well: Bundles in clusters with high arrival rate must wait for a long time to be delivered to the sink node, while less important visits to clusters with a few bundles also take place. In [5], we proposed a scheme to determine an optimal visiting order of a message ferry for one group, which minimizes the *mean delivery delay* of bundles, i.e., the average time interval from the generation of a bundle in a cluster to the completion of its delivery to the sink node. This optimization problem can be reduced to the minimization problem of the weighted mean waiting time in the conventional polling model of queueing theory [12]. The proposed visiting order is effective, especially when arrival rates of bundles in clusters and/or distances between clusters and the sink node are heterogeneous.

When there are lots of distant static clusters with heterogeneous offered load, which is the product of the mean arrival rate and mean service time, there is a potential drawback in designing a route using only one message ferry: The time spent for one cycle of the route increases with the number of clusters. This issue is the main concern of this paper. The whole system is divided into multiple groups, each of which consists of a sink node, clusters, and one message ferry as in Fig. 1.

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[†]The authors are with the Department of Information and Communications Technology, Graduate School of Engineering, Osaka University, Suita, Osaka, 565-0871, Japan.
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a) E-mail: sasabe@comm.eng.osaka-u.ac.jp
b) E-mail: habib@post.comm.eng.osaka-u.ac.jp
c) E-mail: takine@comm.eng.osaka-u.ac.jp
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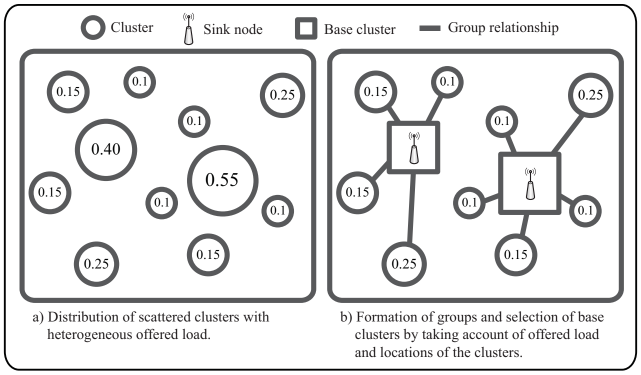

Fig. 1 Example of grouping where each number represents the offered load of each cluster and the size of each cluster is proportional to its offered load.

To decrease the mean delivery delay of bundles, it is desirable to increase the number of groups. However, this also increases the costs to introduce the sink nodes and message ferries, i.e., introduction costs. In general, the system designer aims to minimize the mean delivery delay of bundles under the constraint of the number of groups.

We assume that the sink node is constructed in one of clusters in each group. In what follows, we call a cluster with the sink node a *base cluster* and others *group members*. We further assume that the nodes in each base cluster can directly communicate with their sink node via high speed wireless channels, so that the delivery delay of bundles generated at base clusters are negligible. Therefore, the offered load of the base cluster is excluded from the total offered load in each group. Note here that the total offered load handled by a message ferry should be less than one, and a moderate intensity, say 0.7 or less, is preferable. In Fig. 1, the total offered loads of the left and right groups become 0.65 and 0.7, respectively.

Our main goal is making groups to minimize the mean delivery delay of bundles in all groups under the constraint of the introduction costs. As mentioned above, we studied the minimization problem of the mean delivery delay in a single, fixed group [5], where we obtained an explicit objective function composed of four factors: arrival rates of bundles in clusters, offered loads of clusters, traveling times between clusters and their sink nodes, and the second moment of the bundle-transmission time distribution. Utilizing this result, we model our problem as a nonlinear integer programming and solve it with the help of a commercial nonlinear solver.

Besides, the intra-cluster communication can be efficiently handled by accumulating bundles from cluster members to a limited number of nodes called aggregators, with the help of the self-organized data aggregation technique in our previous work [4]. As a result, the message ferry needs to collect bundles only from the aggregators.

In summary, combining this work with two of our previous works, we can comprehensively achieve effective data aggregation in ferry-assisted multi-clusters DTNs: (i) Making groups and determining base clusters, i.e., sink nodes according to this work, (ii) obtaining a visiting order for each group using the visiting order scheme [5], and (iii) electing aggregators in each cluster based on the self-organized data aggregation technique [4].

The rest of this paper is organized as follows. Section 2 provides the problem formulation. In Section 3, we demonstrate the characteristics of the grouping through numerical results. Finally we conclude the paper in Section 4.

2. Problem formulation

2.1 Overview

Our goal is the development of a method for dividing clusters into several disjoint groups to minimize the overall mean delivery delay of all groups under the constraint of the introduction costs in terms of the number of sink nodes and message ferries. For each group, we select a base cluster, where a sink node is located, and we assign one message ferry to the group. Recall that the sink node has a connection to the outer world and can directly handle traffic generated in the cluster it belongs to via high speed wireless channels. On the other hand, the message ferry goes back and forth between the base cluster and other clusters in order to collect bundles. In general, the overall mean delivery delay of bundles decreases with the increase of the number of groups. In order to restrain the introduction costs, however, it is preferable that the number of message ferries should be minimal under the condition that the overall mean delivery delay is allowable.

Note that given groups, we can calculate an optimal visiting order of clusters to minimize the mean delivery delay of each group, according to [5]. Therefore, we first formulate our problem as an optimization problem whose objective function is the lower bound of the overall mean delivery delay of all groups, when the number K of groups is given. This will be shown as a nonlinear integer programming formulation in section 2.2. We also give a guideline for the number K of groups in section 2.3.

2.2 Nonlinear integer programming formulation

We assume that there are V clusters labeled 1 to V in a closed geographical area. Let $\mathcal{V} = \{1, 2, \ldots, V\}$ denote the set of cluster indices. We define $\boldsymbol{D} = [d_{i,j}]$ $(i, j \in \mathcal{V})$ as a matrix of the message ferry's traveling time $d_{i,j}$ between cluster i and cluster j, where $d_{i,i}$ $(i \in \mathcal{V})$ is equal to zero. Let λ_i $(i \in \mathcal{V})$ denote the

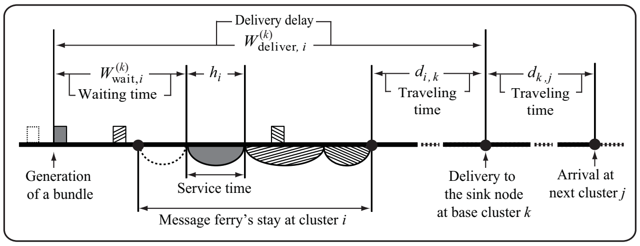

Fig. 2 Timing chart in group k (exhaustive service policy). When the message ferry arrives at cluster i, three bundles have already arrived. During the service for them, one bundle is further generated. When there is no bundle to be served, the message ferry leaves cluster i and visits the next cluster j via the base cluster k.

mean arrival rate λ_i of bundles in cluster i. We assume that transmission times of bundles at cluster i ($i \in \mathcal{V}$) are independent and identically distributed (i.i.d.) according to a general distribution with finite mean h_i and second moment $h_i^{(2)}$. Also, let ρ_i ($i \in \mathcal{V}$) denote the average offered load of cluster i. Note that $\rho_i = \lambda_i h_i$ and ρ_i should be less than one to achieve stable systems.

We assume that base clusters are selected from the subset $\mathcal{U}$ of $\mathcal{V}$ ($\mathcal{U} \subseteq \mathcal{V}$). We define the set of base clusters as $\mathcal{K}$, where $|\mathcal{K}| = K$. Note that $\mathcal{K} \subseteq \mathcal{U} \subseteq \mathcal{V}$. We will discuss a way of setting the number K of groups in section 2.3. Let $\mathcal{V}^{(k)}$ denote the set of group members in group k ($k \in \mathcal{K}$), where k also represents the ID of the corresponding base cluster. Note that base cluster k is excluded from $\mathcal{V}^{(k)}$. Let $\mathrm{E}[W^{(k)}_{\text{total}}]$ denote the mean delivery delay of bundles in group k.

$$\mathrm{E}[W^{(k)}_{\text{total}}] = \frac{\displaystyle\sum_{i\in\mathcal{V}^{(k)}} \lambda_i \mathrm{E}[W^{(k)}_{\text{deliver},i}] + \lambda_k \cdot 0}{\displaystyle\sum_{i\in\mathcal{V}^{(k)}} \lambda_i + \lambda_k} \quad (k \in \mathcal{K}),$$

where the mean delivery delay $\mathrm{E}[W^{(k)}_{\text{deliver},i}]$ is the average time interval from the generation of a bundle of cluster i ($i \in \mathcal{V}^{(k)}$, $k \in \mathcal{K}$) to the completion of its delivery to the sink node in the base cluster at group k (See Fig. 2). Note that the delivery delay of the base cluster k is always zero, which is represented by the second term of the numerator, because it can directly use the high speed wireless channels without the help of the message ferry. The overall mean delivery delay $\mathrm{E}[W_{\text{total}}]$ of bundles becomes

$$\mathrm{E}[W_{\text{total}}] = \frac{\displaystyle\sum_{k\in\mathcal{K}} \lambda^{(k)}_{\text{total}} \mathrm{E}[W^{(k)}_{\text{total}}]}{\displaystyle\sum_{k\in\mathcal{K}} \lambda^{(k)}_{\text{total}}}, \tag{1}$$

where $\lambda^{(k)}_{\text{total}} = \sum_{i\in\mathcal{V}^{(k)}} \lambda_i + \lambda_k$ and $\sum_{k\in\mathcal{K}} \lambda^{(k)}_{\text{total}}$ is constant.

Our main objective is to create groups of clusters in order to minimize $\mathrm{E}[W_{\text{total}}]$. From our previous work [5], $\mathrm{E}[W^{(k)}_{\text{total}}]$ ($k \in \mathcal{K}$) is given by

$$\mathrm{E}[W^{(k)}_{\text{total}}] = \frac{1}{\lambda^{(k)}_{\text{total}}} \sum_{i\in\mathcal{V}^{(k)}} \lambda_i \left(\frac{\mathrm{E}[W^{(k)}_{\text{wait},i}] + h_i}{1-\rho_i} + d_{k,i} \right),$$

where $\mathrm{E}[W^{(k)}_{\text{wait},i}]$ denotes the average waiting time that a randomly chosen bundle at cluster i in group k waits for ferry's service from its generation (See Fig. 2). Under the exhaustive service discipline (i.e., bundles are transmitted successively to the message ferry and the message ferry leaves the cluster only when there are no waiting bundles), the lower bound $\mathrm{E}[W^{(k)}_{\text{total}}]^*$ of $\mathrm{E}[W^{(k)}_{\text{total}}]$ ($k \in \mathcal{K}$) becomes as follows [5]:

$$\begin{aligned}\mathrm{E}[W^{(k)}_{\text{total}}]^* = {} & \frac{1}{2\lambda^{(k)}_{\text{total}}} \sum_{i\in\mathcal{V}^{(k)}} \left(\frac{\lambda_i}{q_i} + \frac{\lambda_i^2 h_i^{(2)}}{(1-\rho_i)^2} \right) \\ & + \frac{1}{\lambda^{(k)}_{\text{total}}} \sum_{i\in\mathcal{V}^{(k)}} \left(\frac{\rho_i}{1-\rho_i} + \lambda_i d_{k,i} \right). \end{aligned} \tag{2}$$

In (2), q_i ($i \in \mathcal{V}^{(k)}$) denotes the mean number of visits at cluster i per unit time at group k ($k \in \mathcal{K}$), i.e.,

$$q_i = \frac{1-\rho^{(k)}_{\text{total}}}{\displaystyle\sum_{j\in\mathcal{V}^{(k)}} \sqrt{2\lambda_j d_{k,j}}} \sqrt{\frac{\lambda_i}{2d_{k,i}}}, \tag{3}$$

where $\rho^{(k)}_{\text{total}} = \sum_{i\in\mathcal{V}^{(k)}} \rho_i$.

From (1), (2), and (3), $\mathrm{E}[W^{(k)}_{\text{total}}]^*$ ($k \in \mathcal{K}$) and the lower bound $\mathrm{E}[W_{\text{total}}]^*$ of $\mathrm{E}[W_{\text{total}}]$ are rewritten to be

$$\mathrm{E}[W^{(k)}_{\text{total}}]^* = (\lambda^{(k)}_{\text{total}})^{-1} f^{(k)}, \tag{4}$$

$$\mathrm{E}[W_{\text{total}}]^* = \lambda^{-1}_{\text{total}} \sum_{k\in\mathcal{K}} f^{(k)}, \tag{5}$$

where

$$\begin{aligned} f^{(k)} = {} & \frac{\left(\displaystyle\sum_{j\in\mathcal{V}^{(k)}} \sqrt{\lambda_j d_{k,j}} \right)^2}{1-\rho^{(k)}_{\text{total}}} + \sum_{j\in\mathcal{V}^{(k)}} \lambda_j d_{k,j} \\ & + \sum_{j\in\mathcal{V}^{(k)}} \left(\frac{\rho_j}{1-\rho_j} + \frac{\lambda_j^2 h_j^{(2)}}{2(1-\rho_j)^2} \right), \end{aligned} \tag{6}$$

$$\lambda_{\text{total}} = \sum_{k\in\mathcal{K}} \lambda^{(k)}_{\text{total}}.$$

We now formulate the minimization problem of the lower bound $\mathrm{E}[W_{\text{total}}]^*$ of the mean delivery delay as an integer programming. We expect that the minimization of $\mathrm{E}[W_{\text{total}}]^*$ will yield a quasi-optimal grouping of clusters.

We first define decision variables $x_{i,j}$ ($i, j \in \mathcal{V}$) as

$$x_{i,j} = \begin{cases} 1, & \text{if } i = j \text{ and cluster } i \text{ is a base cluster,} \\ 1, & \text{if clusters } i \text{ and } j\ (i \neq j) \text{ are in the same} \\ & \text{group and cluster } i \text{ is a base cluster,} \\ 0, & \text{otherwise.} \end{cases}$$

Note that $\mathcal{K}$ and $\mathcal{V}^{(k)}$ $(k \in \mathcal{K})$ are given by

$$\mathcal{K} = \{i;\ x_{i,i} = 1\}, \quad \mathcal{V}^{(k)} = \{j;\ j \neq k,\ x_{k,j} = 1\}.$$

With those decision variables, we can formulate the grouping problem as follows.

$$\begin{aligned} \text{P: min} \quad & \sum_{i \in \mathcal{V}} f^{(i)}(\boldsymbol{X}), & (7) \\ \text{s.t.} \quad & x_{i,i} \in \{0,1\}, \quad \forall i \in \mathcal{U}, & (8) \\ & x_{i,i} = 0, \qquad \forall i \in \mathcal{V} \setminus \mathcal{U}, & (9) \\ & x_{i,j} \in \{0,1\}, \quad \forall i,j \in \mathcal{V},\ i \neq j, & (10) \\ & \sum_{i \in \mathcal{V}} x_{i,j} = 1, \quad \forall j \in \mathcal{V}, & (11) \\ & \sum_{i \in \mathcal{V}} x_{i,i} = K, & (12) \\ & \sum_{j \in \mathcal{V}} \rho_j x_{i,j} - \rho_i x_{i,i} < 1,\ \forall i \in \mathcal{V}, & (13) \end{aligned}$$

where $\boldsymbol{X} = [x_{i,j}]$ denotes the matrix of decision variables and $f^{(i)}(\boldsymbol{X})$ $(i \in \mathcal{V})$ is given by

$$f^{(i)}(\boldsymbol{X}) = \frac{\left(\sum_{j \in \mathcal{V}} \sqrt{\lambda_j d_{i,j}} x_{i,j}\right)^2}{1 - \left(\sum_{j \in \mathcal{V}} \rho_j x_{i,j} - \rho_i x_{i,i}\right)} + \sum_{j \in \mathcal{V}} \lambda_j d_{i,j} x_{i,j} + \sum_{j \in \mathcal{V} \setminus \{i\}} \left(\frac{\rho_j}{1-\rho_j} + \frac{\lambda_j^2 h_j^{(2)}}{2(1-\rho_j)^2}\right) x_{i,j}. \quad (14)$$

Note here that (8) and (9) ensure that base clusters should be selected among $\mathcal{U}$. (8) through (11) mean that cluster j is either a base cluster ($x_{j,j} = 1$) or a group member in the same group as base cluster i ($x_{i,j} = 1$ for $i \neq j$). (12) implies that there are K base clusters. (13) means that the total offered load of each group should be less than one. Note here that for $i \in \mathcal{V}$ such that $x_{i,i} = 0$ (i.e., i is not a base cluster), the left hand sides of (13) is equal to zero, so that (13) always holds for such i. (14) is equivalent to (6), because it is positive only when i is a base cluster ($x_{i,i} = 1$). Since λ_{total} in (5) is constant regardless of $x_{i,j}$, the objective function can be rewritten to be (7).

Because the first term of (14) is nonlinear and the decision variables $x_{i,j}$ are integer, our problem P is a nonlinear integer programming, which can be solved by commercial nonlinear solvers, e.g., KNITRO [7]. Our problem can be regarded as a variant of the capacitated vertex p-center problem (CVPCP) in facility location problems [8, 11]. CVPCP tries to find locations of p capacitated facilities and assign customers to them in order to minimize the longest distance between facilities and their customers, when the locations and capacity of facilities, and locations and demand of customers are given. In our case, the facility and the customer are the sink node and the cluster, respectively. However, the objective function (7) and the constraint (13) are different from the conventional CVPCP.

2.3 Guideline for the number K of groups

To solve problem P, we have to specify the number K of groups. In this subsection, we provide a guideline for it. Given a maximum allowable offered load θ in each group, we can find the lower bound $K_{\text{lower}}(\theta)$ of the number K of groups as follows. Suppose there exist K disjoint, non-empty group partitions for a given maximum allowable offered load θ in each group. Without loss of generality, we assume $\rho_1 \geq \rho_2 \geq \cdots \geq \rho_V$. If cluster i for some $i > K$ is a base cluster of group k, there exists a cluster j ($j \leq K$) of group k'. We then swap those two clusters; cluster j becomes a base cluster of group k and cluster i joins group k' as a group member. This swap yields another feasible group partition because it decreases the total offered load of group k' by $\rho_j - \rho_i > 0$, and when $k \neq k'$, the total offered load of group k remains the same. Therefore, we consider only the case that clusters 1 to K are base clusters in discussing $K_{\text{lower}}(\theta)$ for a while. If a feasible partition of K groups is given, $\rho_{K+1} \leq \theta$ and $\rho_{K+1} + \rho_{K+2} + \cdots + \rho_V \leq K\theta$. We thus have

$$K_{\text{lower}}(\theta) = \min_{1 \leq K \leq V} \{K;\ \rho_{K+1} \leq \theta, \sum_{i=K+1}^{V} \rho_i \leq K\theta\}.$$

Next, we focus on how to determine θ. From the first term of (14), a moderate value of θ, e.g., 0.7, is desirable to avoid the steep increase of the mean delivery delay of bundles. In actual situations, the system designer has to determine K by taking account of the tradeoff between the delivery delay and the introduction costs. This tradeoff problem will be discussed in subsection 3.4.

3. Numerical results

3.1 Evaluation settings

We consider an area of 40 [km] × 40 [km], where fifty isolated clusters ($V = 50$) are randomly located. For inter-cluster communications, we assume that each message ferry travels at a fixed speed of 10 m/s (i.e., 36 km/h). We then set $\boldsymbol{D} = [d_{ij}]$ $(i,j \in \mathcal{V})$ by dividing the distance between cluster i and cluster j by the ferry's speed.

We assume that the mean arrival rate λ_i $(i \in \mathcal{V})$ of bundles at cluster i is given by $0.01 \times i$. We also assume that transmission times of bundles in cluster i $(i \in \mathcal{V})$ are i.i.d. according to an exponential distribution with

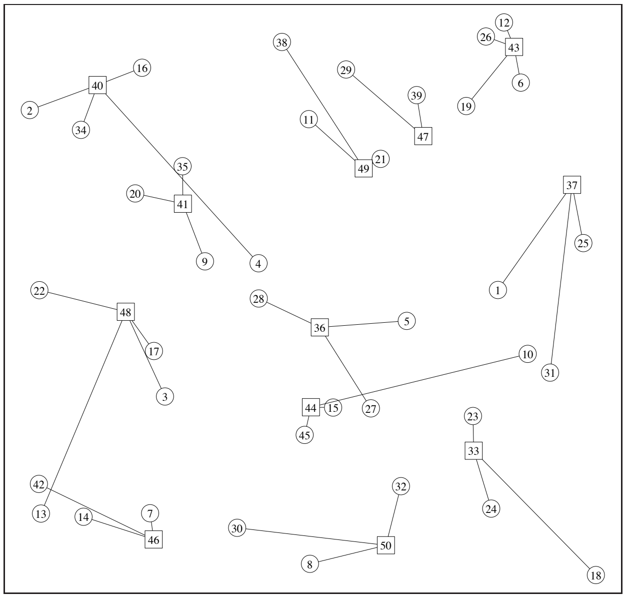

Fig. 3 Quasi-optimal grouping ($K = 12$, $\mathcal{U} = \mathcal{V}$, Case 1).

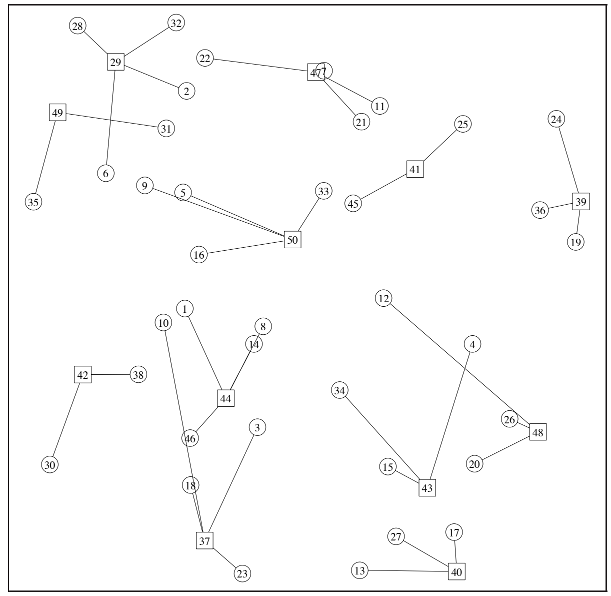

Fig. 4 Quasi-optimal grouping ($K = 12$, $\mathcal{U} = \mathcal{V}$, Case 2).

Table 1 Settings of ρ_i (V=50).

ρ_1	ρ_2	ρ_3	$\cdots$	ρ_{50}	$\overline{\rho}$
0.01	0.02	0.03	$\cdots$	0.50	0.255

mean $h_i = 1$ [s] and second moment $h_i^{(2)} = 2$. We then have $\rho_i = \lambda_i$ ($i \in \mathcal{V}$), as shown in Table 1. Note that ρ_i is assigned in an ascending order with cluster IDs, and the mean offered load is given by 0.255. We set $K = K_{\text{lower}}(0.7) = 12$, unless stated otherwise.

We obtain the quasi-optimal grouping by solving P using a nonlinear solver KNITRO. Next, we derive $\text{E}[W_{\text{total}}^{(k)}]^*$ ($k \in \mathcal{K}$) and determine the optimal visiting order of the message ferry in each group according to the method in [5]. Finally, we conduct the simulation experiments to obtain $\text{E}[W_{\text{total}}^{(k)}]$ for each group k ($k \in \mathcal{K}$) and calculate the overall mean delivery delay $\text{E}[W_{\text{total}}]$.

3.2 Fundamental characteristics

We first examine fundamental characteristics of grouping obtained by solving the optimization problem. We set $\mathcal{U} = V$ and $K = 12$, and used two random cluster layouts: Case 1 in Fig. 3 and Case 2 in Fig. 4. In these figures, the solution of problem P is also represented, where circles, squares, and lines indicate the base clusters, the group members, and the group relationship, respectively. Tables 2 and 3 shows the group-level results of optimization in Cases 1 and 2, respectively. For each group, we show the base cluster's ID, $\rho_{\text{total}}^{(k)}$, $d_{\text{total}}^{(k)}$, $\text{E}[W_{\text{total}}^{(k)}]^*$, and $\text{E}[W_{\text{total}}^{(k)}]$, where $d_{\text{total}}^{(k)}$ denotes the total distance between base cluster k ($k \in \mathcal{K}$) and its group members.

Clusters with larger IDs tend to be base clusters because the offered load ρ_k of base cluster k is excluded from the total offered load of group k. Selecting the highly loaded clusters as base clusters leads to small $\text{E}[W_{\text{total}}]$. In the case of $K = 12$, the top 12 of highly loaded clusters are clusters 39–50, among which only clusters 39, 42, and 45 in Case 1 and only clusters 41 and 45 in Case 2 are not base clusters. Also, as discussed in section 2.3, the total offered load in each group should be moderate (see Tables 2 and 3).

Next, we discuss the influence of $d_{i,j}$ ($i, j \in \mathcal{V}$). Intuitively, short distances between a base cluster and its group members are preferable. Recall that the objective function is given by the sum of $f^{(i)}(\boldsymbol{X})$ ($i \in \mathcal{V}$). It follows from (14) that $f^{(i)}(\boldsymbol{X})$ is positive iff $x_{i,i} = 1$. Therefore, for $i, j \in \mathcal{V}$ such that $x_{i,i} = 1$ and $x_{i,j} = 1$, $f^{(i)}(\boldsymbol{X})$ is an increasing function of $\lambda_j d_{i,j}$ ($= \rho_j d_{i,j}$ because $h_j = 1$ in our setting). We thus have to take account of the offered load ρ_j, as well as $d_{i,j}$. This is the reason why some clusters with low arrival rates (e.g., clusters 4, 10, and 13 in Case 1, and clusters 10 and 12 in Case 2) belong to distant base clusters. We also observe in Figs. 3 and 4 that above-mentioned highly loaded group members (i.e., clusters 39, 42, and 45 in Case 1 and clusters 41 and 45 in Case 2) are located next to other highly loaded clusters. As a result, each group has relatively low total offered load and/or relatively short total distance (see Tables 2 and 3).

Finally, Table 4 illustrates the overall results of optimization: Arithmetic means of $\rho_{\text{total}}^{(k)}$ and $d_{\text{total}}^{(k)}$, $\text{E}[W_{\text{total}}]^*$ in (5) and $\text{E}[W_{\text{total}}]$ obtained by simulation experiments. Because both cases show the similar results, we use the cluster layout of Case 1 in the succeeding evaluations.

Table 2 Group-level results of optimization ($K = 12$, $\mathcal{U} = \mathcal{V}$, Case 1).

Base cluster	33	36	37	40	41	43	44	46	47	48	49	50
$\rho^{(k)}_{\text{total}}$	0.65	0.60	0.57	0.56	0.64	0.63	0.70	0.63	0.68	0.55	0.70	0.70
$d^{(k)}_{\text{total}}$	1,853	1,722	2,592	2,803	1,018	1,162	1,881	1,564	985	3,089	1,677	1,985
$\text{E}[W^{(k)}_{\text{total}}]^*$	3,379	2,728	3,264	2,251	1,695	1,883	2,289	2,824	1,944	3,424	3,381	3,945
$\text{E}[W^{(k)}_{\text{total}}]$	3,885	3,010	3,593	2,570	1,803	2,024	3,199	2,966	2,349	3,717	3,648	4,160

Table 3 Group-level results of optimization ($K = 12$, $\mathcal{U} = \mathcal{V}$, Case 2).

Base cluster	29	37	39	40	41	42	43	44	47	48	49	50
$\rho^{(k)}_{\text{total}}$	0.68	0.54	0.79	0.57	0.70	0.68	0.53	0.69	0.61	0.58	0.66	0.63
$d^{(k)}_{\text{total}}$	2,233	3,240	1,203	1,474	973	1,080	2,332	2,100	1,853	2,186	1,444	3,061
$\text{E}[W^{(k)}_{\text{total}}]^*$	3,911	3,364	3,879	2,165	2,324	2,334	2,602	2,918	2,874	2,458	2,837	3,912
$\text{E}[W^{(k)}_{\text{total}}]$	4,336	3,729	4,175	2,376	2,523	2,606	2,888	3,052	3,061	2,823	2,855	3,994

Table 4 Overall results of optimization ($K = 12$, $\mathcal{U} = \mathcal{V}$).

	mean of $\rho^{(k)}_{\text{total}}$	mean of $d^{(k)}_{\text{total}}$	$\text{E}[W_{\text{total}}]^*$	$\text{E}[W_{\text{total}}]$
Case 1	0.63	1,860	2,756	3,084
Case 2	0.64	1,931	2,970	3,201

Table 5 Relationship between $|\mathcal{U}|$ and overall results of optimization ($K = 12$, Case 1).

$\lvert\mathcal{U}\rvert$	mean of $\rho^{(k)}_{\text{total}}$	mean of $d^{(k)}_{\text{total}}$	$\text{E}[W_{\text{total}}]^*$	$\text{E}[W_{\text{total}}]$
12	0.62	2,516	3,370	3,680
13	0.62	2,568	3,367	3,678
14	0.62	2,323	3,073	3,390
15–17	0.62	2,175	3,044	3,336
≥ 18	0.63	1,860	2,756	3,084

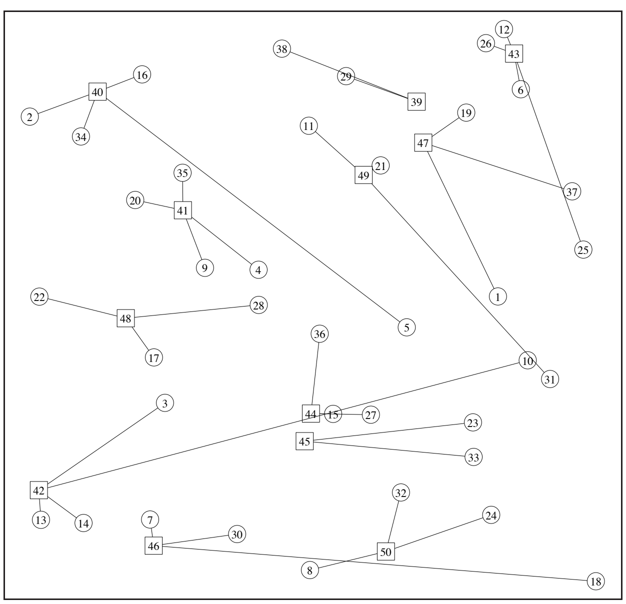

Fig. 5 Quasi-optimal grouping ($K = 12$, $|\mathcal{U}| = 12$, Case 1).

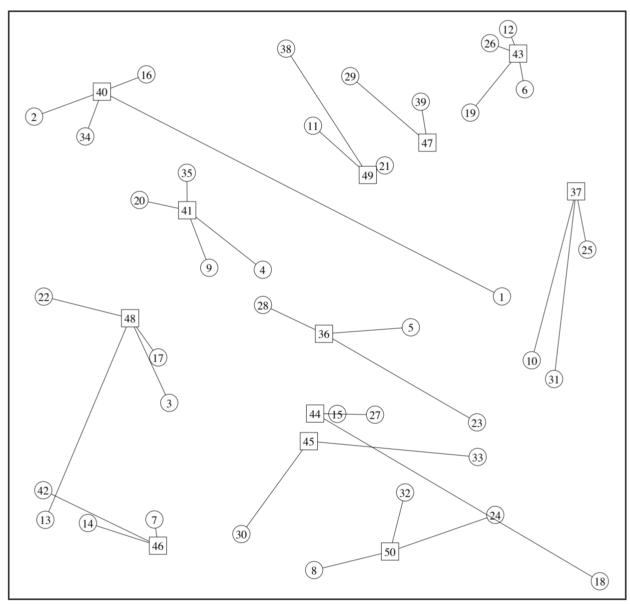

Fig. 6 Quasi-optimal grouping ($K = 12$, $|\mathcal{U}| = 15$, Case 1).

3.3 Impact of location limitation of base clusters

In this subsection, we examine how the location limitation $\mathcal{U}$, i.e., the candidates of base clusters, affects $\text{E}[W_{\text{total}}]$. In actual situations, the system designer may not be able to select the locations of base clusters freely due to some economical and/or geographical reasons. For instance, highly populated clusters may have higher priority than others. Because the arrival rate of bundles at a cluster seems to have positive correlation with the population of that cluster in actual situations,

Table 6 Tradeoff between overall results and K ($\mathcal{U} = \mathcal{V}$, Case 1).

K	mean of $\rho^{(k)}_{\text{total}}$	mean of $d^{(k)}_{\text{total}}$	$\text{E}[W_{\text{total}}]^*$	$\text{E}[W_{\text{total}}]$
11	0.72	2,199	4,451	4,826
12	0.63	1,860	2,756	3,084
13	0.55	1,462	2,010	2,209

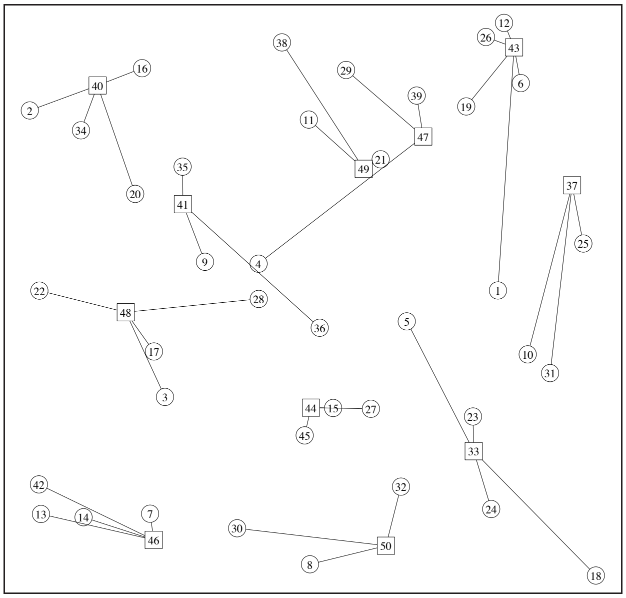

Fig. 7 Quasi-optimal grouping ($K = 11$, $\mathcal{U} = \mathcal{V}$, Case 1).

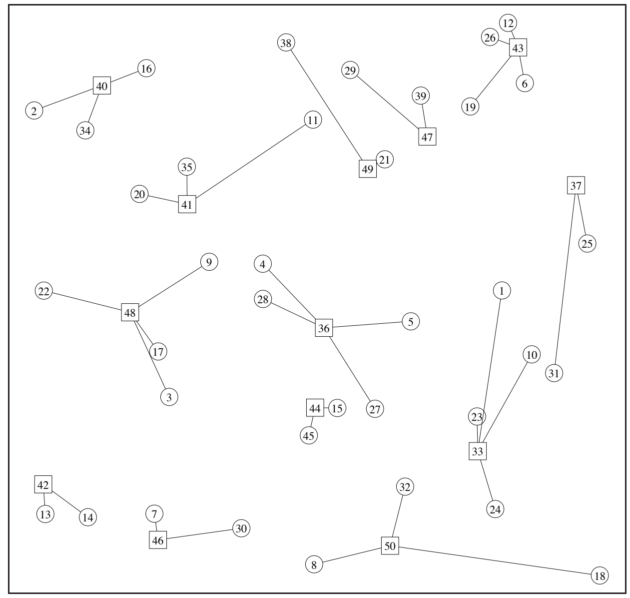

Fig. 8 Quasi-optimal grouping ($K = 13$, $\mathcal{U} = \mathcal{V}$, Case 1).

we assume that $\mathcal{U}$ consists of the top $|\mathcal{U}|$ highly loaded clusters in this subsection.

Table 5 illustrates the relationship between $|\mathcal{U}|$ and the results of optimization when $K = 12$. We also show the quasi-optimal grouping for $|\mathcal{U}| = 12$ and $|\mathcal{U}| = 15$ in Figs. 5 and 6, respectively. Note that the results for $|\mathcal{U}| = 15, 16,$ and 17 are identical and all results for $|\mathcal{U}| \geq 18$ are identical to the case of $\mathcal{U} = \mathcal{V}$. Comparing Figs. 5 and 6 with Fig 3, we observe that some clusters have to be assigned to very distant base clusters when $K = 12$ and 15. As a result, $\text{E}[W_{\text{total}}]$ becomes large. In Case 1, cluster 33, which can be selected as a base cluster only when $|\mathcal{U}| \geq 18$, plays an important role in minimizing $\text{E}[W_{\text{total}}]$.

3.4 Tradeoff between delivery delay and introduction costs

So far, we set $K = 12$, which was obtained by setting $\theta = 0.70$ in the procedure of subsection 2.3. In this subsection, we discuss the tradeoff between $\text{E}[W_{\text{total}}]$ and the introduction costs proportional to K. Table 6 shows the results of optimization for $K = 11$, 12, and 13, where $\mathcal{U} = \mathcal{V}$. We also show the quasi-optimal grouping for $K = 11$ and $K = 13$ in Figs. 7 and 8, respectively.

As we expected, $\text{E}[W_{\text{total}}]$ decreases with the increase of K because of the reduction of both $\rho^{(k)}_{\text{total}}$ and $d^{(k)}_{\text{total}}$. We further observe that the difference between $\text{E}[W_{\text{total}}]$ of $K = 11$ and that of $K = 12$ is larger than the difference between $\text{E}[W_{\text{total}}]$ of $K = 12$ and that of $K = 13$. This is because the first term of (14) has a larger impact when its denominator, i.e., total offered load, approaches one.

4. Conclusion

In this paper, we considered grouping of clusters in ferry-assisted DTNs in order to minimize the overall mean delivery delay of bundles. We first formulated our problem as a nonlinear integer programming, which depends on the arrival rate and offered load of clusters, the transmission time distribution of bundles, and the distance between clusters. By solving the optimization problem using the nonlinear solver KNITRO, we obtained the quasi-optimal grouping. Through numerical evaluations, we showed the basic characteristics of grouping, the impact of location limitation of base clusters, and the tradeoff between delivery delay and introduction costs.

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Masahiro Sasabe is currently an Assistant Professor with the Department of Information and Communication Technology, Osaka University. He received the M.E. and Ph.D. degrees from Osaka University, Osaka, Japan, in 2003 and 2006, respectively. From 2003 to 2004, he was a Research Fellow with 21COE-JSPS, Japan. From 2004 to 2007, he was an Assistant Professor with the Cybermedia Center, Osaka University. His research interests include P2P/overlay networking, DTNs, and game-theoretic approach. Dr. Sasabe is a member of IEEE.

K. Habibul Kabir received B.Eng. in electrical and electronics engineering from Islamic University of Technology (IUT), Bangladesh, in 2002. He received M.Eng. in electrical, electronic and information system engineering, and Dr.Eng. degree from Osaka University, Japan, in 2007, 2012, respectively. He joined as a Lecturer in the Electrical and Electronics Engineering Department of Islamic University of Technology, Bangladesh in 2002, and till date he is on leave of absence from the university. His research interests include design and performance evaluation of delay tolerant networks. Dr. Kabir is a member of IEEE.

Tetsuya Takine is currently a Professor in the Department of Information and Communications Technology, Graduate School of Engineering, Osaka University, Suita, Japan. He was born in Kyoto, Japan, on November 28, 1961, and received B.Eng., M.Eng., and Dr.Eng. degrees in applied mathematics and physics from Kyoto University, Kyoto, Japan, in 1984, 1986, and 1989, respectively. In April 1989, he joined the Department of Applied Mathematics and Physics, Faculty of Engineering, Kyoto University, as an Assistant Professor. Beginning in November 1991, he spent one year at the Department of Information and Computer Science, University of California, Irvine, on leave of absence from Kyoto University. In April 1994, he joined the Department of Information Systems Engineering, Faculty of Engineering, Osaka University as a Lecturer, and from December 1994 to March 1998, he was an Associate Professor in the same department. From April 1998 to May 2004, he was an Associate Professor in the Department of Applied Mathematics and Physics, Graduate School of Informatics, Kyoto University. His research interests include queueing theory, emphasizing numerical computation, and its application to performance analysis of computer and communication networks. He is now serving as an area editor of Operations Research Letters and an associate editor of Queueing Systems, Stochastic Models, and International Transactions in Operational Research. He received Telecom System Technology Award from TAF in 2003, Best Paper Awards from ORSJ in 1997, from IEICE in 2004 and 2009, and from ISCIE in 2006, and Best Tutorial and Magazine Awards from IEICE ComSoc in 2012. Dr. Takine is a fellow of ORSJ and a member of IEEE, IPSJ, and ISCIE.