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LETTER

Game theory approach for autonomous mobility-assisted Piggyback network with mm-wave links

Daisuke Yamamoto[1], **So Hasegawa**[2], **Yozo Shoji**[2], **and Mikio Hasegawa**[1, a)]

Abstract A Piggyback network, which is a store-carry-forward network organized by working mobilities of delivery trucks and serving robots, realizes a large-scale data distribution platform. However, when the working mobilities participate in the Piggyback network, the data carrying and forwarding tasks influence their original tasks, resulting in additional transfer costs necessitating appropriate data transfer management. This study proposes a data-transfer management scheme in the Piggyback network. We have developed an algorithm based on the Stackelberg game to balance the end-to-end throughput and the cost required by working mobilities for each data delivery, and we have formulated a rule for the users to select the best mobility based on the balanced throughput and costs. The simulation results show that the proposed method maximizes the utility and achieves a high average throughput of the entire network.

Keywords: Piggyback network, store-carry-forward network, game theory, Stackelberg game
Classification: Wireless communication technologies

1. Introduction

High-speed data collection and transfer technologies for large-scale data are essential with the recent spread of large-scale data applications and services. Using existing cellular networks for high-capacity data transfer causes overload and congestion. Moreover, extending new facilities may quickly exceed cost and capacity limits. Therefore, it is necessary to develop a novel high-capacity data transfer method.

A Piggyback network has been proposed as a data distribution platform based on a store-carry-forward (SCF) mechanism consisting of working mobilities, such as delivery trucks and serving robots [1]. This scheme has the potential to achieve higher throughput than existing infrastructure-based data transfers when transferring extremely large-scale data by equipping the mobilities with high-speed wireless communication such as millimeter waves or terahertz links. Shoji *et al.* [2] evaluated the data distribution performance of the Piggyback network based on actual mobility trajectory and showed that it could distribute data to the community in a short time. Hasegawa *et al.* [3] proposed an optimization method for task allocation and mobility routing for multiple distributed data transfer requests in the Piggyback network and showed that it achieved high throughput performance. However, local autonomous mobilities, such as taxis and delivery robots entrusted with data transmission in the Piggyback network, may have their own original tasks. Thus, participating in the Piggyback network data transfer might cause delays in their original tasks and incurs new transfer costs. Therefore, we need an appropriate transfer management method.

This study proposes a data transfer optimization algorithm for maximizing the utility for both autonomous mobilities and users. We analyze the mutual interference of the profits and costs between the mobility entrusted with data transfer and the users requesting the data transfer in the Piggyback networks. We develop an optimization algorithm using the Stachelberg game based on the utility for mobilities and users.

2. System model

We assume a Piggyback network system consisting of I users requesting data and M working mobilities in a defined area, as shown in Fig. 1. The working mobility $m \in M$ and the transfer request $i \in I$ are placed within the defined area. To satisfy the transfer requests from user i, the mobility m carries the assigned data from the source, moves at velocity V_m, and sends the data to the destination. We define the minimum distance between transfer request i and mobility m as $d_{m,i}$. We assume that the working mobilities have their original tasks. Thus, an appropriate transfer management method is necessary to maximize efficiency, such as the transmission time and additional costs.

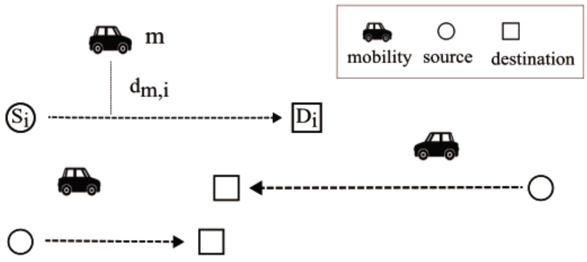

Fig. 1 System model.

3. Interference coordination strategies

In this section, we propose an algorithm to balance the end-

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[1] Department of Electrical Engineering, Tokyo University of Science, 6-3-1 Niijuku, Katsushika-ku, Tokyo 125-8585, Japan
[2] Social-ICT System Laboratory, National Institute of Information and Communications Technology, 4-2-1, Nukui-Kitamachi, Koganei, Tokyo, 184-8795, Japan
[a)] hasegawa@ee.kagu.tus.ac.jp

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to-end throughput and the cost required by the working mobilities for each data delivery. This algorithm is developed based on the Stackelberg game. Using the balanced throughput and costs, we define a selection algorithm for choosing a mobility for each user.

3.1 Formulation of the game

The mutual interaction between the mobility and the users were modeled by the Stackelberg game [4]. We assumed that the tasks of the working mobilities take precedence over data transfer for the Piggyback network. Therefore, the mobilities were formulated as the leader and the users as the follower in the Stackelberg game. The users need to request the data transfer to the mobilities to receive the data. As a leader, the mobilities could charge users who request data transfers. In particular, we assume that the hardware resources in the mobility are limited and problematic. Therefore, we define the following utility functions in this paper to explore how data size impacts participation in the game. The users, as followers, will decide the data size by maximizing the utility function, which corresponds to the difference between the data transfer time and its cost charged by the working mobility. The working mobilities, as leaders, will decide the price using the users' data size by maximizing the utility, which corresponds to the difference between the profit and the transfer cost. The Stackelberg equilibrium will be a balanced data size that should be sent over the Piggyback network and the balanced price to transmit data.

At the leader, the working mobilities adjusted the price for data transfer to maximize its utility function, and collect the payments from the users in the network. Let λ_m be the data transfer price that mobility m obtained by transferring data. We define the utility function of mobility as the difference between the total profit and the moving cost needed for the requested transfer.

$$U^{\mathrm{L}}_m(\lambda_m, \mathbf{S}) = \sum_{i=1}^{I} (\lambda_m S_{m,i} - \varepsilon_m S_{m,i}) x_{m,i}, \tag{1}$$

where $S_{m,i}$ is the transferred data size from mobility m to user i, and ε_m is the transfer cost at mobility m and $x_{m,i}$ is a binary variable such that if mobility m transfers data to user i, then $x_{m,i} = 1$; otherwise, $x_{m,i} = 0$. Here, we assumed the transfer cost depends on the data size. The optimization problem for the leader is to maximize the utility function $U^{\mathrm{L}}_m(\lambda_m, \mathbf{S})$ by tuning the charging price λ_m and is expressed by the following equation:

$$\underset{\lambda_m}{\text{maximize}}\ U^{\mathrm{L}}_m(\lambda_m, \mathbf{S}), \quad \text{s.t} \ \sum_{i=1}^{I} S_{m,i} \leq C_m, \tag{2}$$

where C_m is the cache capacity of the mobility m.

At the follower, the utility function was defined as the difference between the time saved by the mobility's transfer in the Piggyback network and the charge paid to the mobility.

$$U^{\mathrm{F}}_{i,m}(\lambda_m, S_{m,i}) = \ln\left(1 + \frac{S_{m,i}}{R_{BS}} - \left(\frac{d_{m,i}}{V_m} + \frac{S_{m,i}}{R_{mm}}\right)\right) - \lambda_m S_{m,i}, \tag{3}$$

where R_{BS} is the data rate of cellular links from the base station, R_{mm} is the data rate of mm-wave links. The first term is the user satisfaction function [5], which corresponds to the transmission time saved by the Piggyback network data transfer compared to the cellular link, and the second term is the transmission charge paid to the mobility. The optimization problem for the follower is to maximize this utility by selecting appropriate data size and is expressed by the following equation:

$$\underset{S_{m,i}}{\text{maximize}}\ U^{\mathrm{F}}_{i,m}(\lambda_m, S_{m,i}), \quad \text{s.t} \ S_{m,i} \geq s_i, \tag{4}$$

where s_i is the size of the data, which the user i requested to transmit. The equilibrium solution of this game is derived by backward induction, which maximizes the leader's decision after accounting for the follower's reaction [6].

After the update of $S_{m,i}$ and λ_m by Stackelberg game, the user select a mobility corresponding to the highest utility and update $x_{m,i}$ as follows,

$$x_{m,i} = \begin{cases} 1 & (\text{if } m = \underset{l}{\text{argmax}}\ U^{\mathrm{F}}_{i,l}(\lambda_l, S_{l,i})) \\ 0 & (\text{otherwise}) \end{cases} \tag{5}$$

3.2 Follower solution

The users aim maximize their utility $U^{\mathrm{F}}_{i,m}(\lambda_m, S_{m,i})$ under the conditions specified by the leader. To realize this, it is necessary to derive the optimal data size from the mobillity that satisfies the user's transfer requirements as defined in Eq. (3). We calculated the first-order derivative of $U^{\mathrm{F}}_{i,m}(\lambda_m, S_{m,i})$ with respect to $S_{m,i}$ and obtained the following equation:

$$\frac{\partial U^{\mathrm{F}}_{i,m}(\lambda_m, S_{m,i})}{\partial S_{m,i}} = \frac{B}{A_{m,i} + B S_{m,i}} - \lambda_h, \tag{6}$$

where $A_{m,i} = 1 - d_{m,i} x_{m,i} / V_m$ and $B = 1/R_{BS} - x_{m,i}/R_{mm}$. Then, we calculated the second-order derivative of $U^{\mathrm{F}}_{i,m}(\lambda_m, S_{m,i})$ with respect to $S_{m,i}$ and obtained the following equation:

$$\frac{\partial^2 U^{\mathrm{F}}_{i,m}(\lambda_m, S_{m,i})}{\partial S^2_{m,i}} = \frac{-B}{(A_{m,i} + B S_{m,i})^2} < 0, \tag{7}$$

Thus, $U^{\mathrm{F}}_{i,m}(\lambda_m, S_{m,i})$ is clearly a concave function, and we can determine the optimal strategy by solving $\frac{\partial U^{\mathrm{F}}_{i,m}(\lambda_m, S_{m,i})}{\partial S_{m,i}} = 0$. The optimal strategy $S^{\star}_{m,i}$ can be obtained as follows:

$$S^{\star}_{m,i} = \frac{1}{\lambda_m} - \frac{A_{m,i}}{B}. \tag{8}$$

3.3 Leader solution

After obtaining the solution of the transfer data size $S^{\star}_{m,i}$ for each user using Eq. (7), we substituted the solution into the leader's utility function to obtain the optimal price λ_m. The optimization problem for the leader in Eq. (4) is expressed in the following equation using the Lagrange method:

$$L(\lambda_m, \mu_m) = \sum_{i=1}^{I} (\lambda_m S_{m,i} - \varepsilon_m S_{m,i}) - \mu_m \left(C_m - \sum_{i=1}^{I} S_{m,i}\right), \tag{9}$$

where μ_m is the Lagrange multiplier. The dual function is obtained by maximizing the Lagrange function at λ_m. By substituting Eq. (7) into the Lagrange function in Eq. (8) and calculating $\frac{\partial L(\lambda_m,\mu_m)}{\partial \lambda_m} = 0$, the optimal price solution was derived as follows:

$$\lambda_m^{\star} = \left[\sum_{i=1}^{I} \left(\frac{(\varepsilon_m - \mu_m)B}{A_{m,i}} \right)^{1/2} \right]^{+}, \tag{10}$$

The dual problem can be defined by the minimization of the dual function at the Lagrange multiplier μ_m. We utilized the gradient method to find μ_m iteratively [7]. At each iteration t, we updated the μ_m as follows:

$$\mu_m^{t+1} = \mu_m^t - \eta \cdot \left[\sum_{i=1}^{I} \left\{ \left(\frac{A_{m,i}}{(\varepsilon_m - \mu_m^t)B} \right)^{\frac{1}{2}} - \frac{A_{m,i}}{B} \right\} - C_m \right]. \tag{11}$$

where η is the step size.

3.4 Proposed algorithm

Here, we proposed an algorithm that autonomously adjusts interference between the mobility and users based on the Stackelberg equilibrium solution to optimize data transfer in the Piggyback network. The overall algorithm flow is shown in Algorithm 1. The algorithm selected the optimal price and data size based on the equilibrium solution and then selected the mobility with better throughput. The throughput is calculated using the route optimization method proposed in [3]. This process was repeated until the solution is converged and a stable solution is finally obtained.

Algorithm 1 Stackelberg game-based mobility selection algorithm

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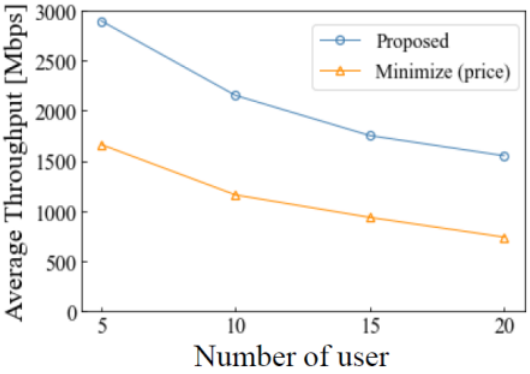
Require: Position of mobility and data, User $i$ requested data size $s_i$.
Ensure: Throughput $T_{m,i}$ from $m$ to $i$, Binary variable $x_{m,i}$.
    Initialization : $\lambda_m^{best}, T_i^{best} = \infty$
while not converge (loop $t$) do
    for $i = 1$ to $I$ do
        for $m = 1$ to $M$ do
            while not converge (loop $step$) do
                Find the price $\lambda_m^*$
                Update the variable $\mu_m$
                Find the optimal data size $S_{m,i}^*$ in helper $m$
            end while (loop $step$)
            if $\lambda_m^* \le \lambda_m^{best} \cap s_i \le S_{m,i}^*$ then
                Calculate Throughput $T_{m,i}$ from $m$ to $i$
                if $T_{m,i} \le T_i^{best}$ then
                    $x_{m,i} = 1, T_i^{best} = T_{m,i}$
                else
                    $x_{m,i} = 0$
                end if
            end if
        end for
    end for
end while (loop $t$)
```

4. Simulation evaluation

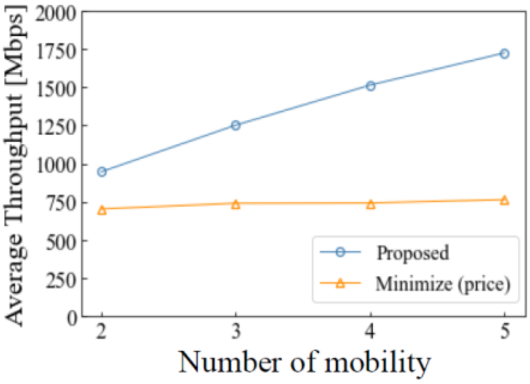
In this section, we evaluated the end-to-end throughput performance of the optimized Piggyback network based on game theory. We assume that the proposed method will be executed by an orchestrator that monitors the entire network. In the simulation, the positions of autonomous mobilities and transfer requests were uniformly distributed within a square of 200 m per side. We compared the throughput performance of the proposed method that optimizes data transfer based on game theory with a method that aims to minimize the transfer cost (Minimize(price)). As simulation parameters, we assumed the user i requested data size s_i is 10 GBytes, the cache capacity C_m of the mobility m is 1 TBytes, the data rate of mm-wave links R_{mm} is 10 Gbps, and the velocity of the mobility m, V_m, is 20 km/h. The evaluation index is the end-to-end throughput R in the entire network, as shown in Eq. (12).

$$R = \frac{\sum_{i=1}^{I} s_i}{\sum_{m=1}^{M} \sum_{i=1}^{I} T_{m,i} x_{m,i}}, \tag{12}$$

Figure 2(a) shows the relationship between the number of users and the average throughput when there are 5 mobilities. Figure 2(b) shows the relationship between the number of mobilities and the average throughput when there are 20 users. The results in Fig. 2(a) show that the proposed method achieves higher average throughput than the method that only considers the minimization of the total charge paid by the users. Furthermore, Fig. 2(b) shows that the effectiveness of the proposed method increases in cases with many mobilities. It is because the proposed scheme can distribute the mobility selection through balanced data transfer charges.



(a) Number of working mobilities is 5.



(b) Number of users is 20.

Fig. 2 Average throughputs of the Piggyback network optimized by the proposed method.

5. Conclusion

In the Piggyback networks, the working mobilities with their original tasks will participate in the data transfer community. Thus, the data transfer speed and the additional costs for the working mobilities to carry the data must be considered. In this study, we propose a method based on the Stackelberg game to analyze and coordinate the mutual interference between the costs and charges of the mobilities for the users requesting the data transfer. The simulation results confirmed that the proposed method provided optimal solutions for both working mobilities and users and improved the data transfer throughput in the Piggyback network. At this stage, we defined individual utility functions for each leader and follower to simplify the problem and proposed a method to coordinate their optimal reactions using a heuristic algorithm. Considering an optimization method for the entire network requires defining utility functions for each set of leaders and followers. In our future work, we aim to address more complex issues, including constraints such as energy consumption of the mobilities and waiting time of the users. Additionally, we plan to develop an exact solution method to derive the optimal solution for the entire network.

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