Optimization of End-to-End Throughput on Piggyback Network with drone-to-drone millimeter-wave communications

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***Abstract*—A store-carry-forward network, incorporating high-speed wireless links and autonomous mobility, such as drones, enables significantly faster data transfer compared to conventional wide-area wireless networks. It has been referred to as a Piggyback Network and proposed as a key technology for Beyond 5G. Recent experiments have successfully demonstrated drone-to-drone direct communication using millimeter waves. This paper proposes an optimization method designed to maximize the throughput of the Piggyback network, which includes multiple data source nodes, destination nodes, and multiple drones equipped with millimeter communication links. We assume that high-speed communications among drones utilizing millimeter waves are available. We optimize the assignment of each transmitted data to drones, the paths of moving drones, and the routing of each data among multiple drones to minimize end-to-end data transfer time. Our simulation results indicate that introducing drone-to-drone millimeter-wave communication leads to faster data transport compared to the conventional Piggyback network.**

Keywords—Piggyback Network, Beyond 5G, store-carry-forward, Autonomous Mobilities, Millimeter wave

I. INTRODUCTION

Drone-based communications are expected to be one of the key technologies that contribute to enabling the Beyond 5G society [1]. There are some examples that use the drone as a BS or acting as an aerial platform to communicate with a set of ground users [2]. Piggyback Network [3-5] has been proposed to enable high-speed and long-distance end-to-end communication for large-size data such as Gigabytes or Terabytes order. This is a data transfer system that uses communication systems such as millimeter wave and store-carry-forward (SCF) routing through mobility movements. Millimeter wave communications support high-speed data transmission over 10Gbps [6], but only for short-distance communication links. Mobility equipped with short-distance millimeter wave communications transfers data by moving from source to destination.

In Ref. [3], the throughput performance of the Piggyback Network using a millimeter wave communication system has already been demonstrated by calculation. The performance has also been evaluated using actual autonomous mobility trajectory data. Ref. [4] describes a passing-by communication method for the Piggyback network and shows that the communication capacity between mobiles can be extended by controlling mobility with a "Stop/Slow-down & Go" policy.

Ref. [5] has proposed optimization algorithms to minimize data transfer time in Piggyback networks. This algorithm optimizes data assignments to drones and the paths of each drone, but it does not include drone-to-drone communication links since it is difficult to formulate as an optimization problem. The optimization problem has been formulated based on a pick-up-and-delivery problem, and a heuristic algorithm has been applied to obtain solutions. Although Ref. [5] clearly showed that the Piggyback network enables much faster end-to-end data delivery, especially for large-size data, it does not include further improvement using drone-to-drone communication.

Ref. [7] has succeeded in actual experiments in millimeter-wave communication among flying drones. They have conducted millimeter wave communications between drones in three different flight modes: drone-to-air, passing-by, and following flight, and have succeeded in establishing communication links and transmitting data.

In this paper, we propose an optimization method to maximize the throughput of the Piggyback network composed of multiple data source nodes, destination nodes, and multiple drones equipped with millimeter communication links, and high-speed communications among the drones using millimeter waves are available. We formulate a problem to optimize each transmission data assignment to drones, paths of moving drones, and routing of each data among the multiple drones to minimize end-to-end data transfer time. We evaluate the obtained solutions of the formulated optimization problem and discuss the effectiveness of introducing drone-to-drone millimeter wave communication to the Piggyback networks.

II. PIGGYBACK NETWORK

Fig. 1 shows an example of Piggyback Network communication. In the Piggyback Network, a drone first approaches the source node and receives transmitted data from the source node via high-speed communication links such as millimeter wave communication. Next, the drone moves to the destination node and transmits the data to the destination node using the high-speed communication link. TransferJet X and other standards are envisioned as millimeter wave communication methods. This is an IEEE 802.15.3e compliant standard that uses the 60GHz band and is capable of high-speed data transfer at speeds of 10Gbps or higher over distances of up to approximately 10m [6].

In general, the time required to deliver M [bit] data by wireless communication link whose data rate is R_1 [bps] is

$$T_1 = \frac{M}{R_1}. \tag{1}$$

Therefore, the end-to-end communication time in the Piggyback Network to deliver M [bit] data to the destination d [m] far from the source node using a drone equipped with R_2 [bps] millimeter wave communication link is

$$T_2 = \frac{2M}{R_2} + \frac{d}{V}, \tag{2}$$

where V[m/h] is the speed of the drone.

From Eqs. (1) and (2), the data delivery time depends only on the size of data in general wireless communication systems, while the data delivery time also depends on the distance in the Piggyback Network. Millimeter wave communication has shorter transmission distances and higher speed characteristics than normal communication methods, therefore the increase in data transfer rate of Piggyback Network relative to the data size is gradual. Due to this, the Piggyback Network is more suitable than regular communication methods for transferring large amounts of data. For example, when $M = 10$ [GB], $d = 2$ [km], $R_1 = 100$ [Mbps], $R_2 = 10$ [Gbps], $V = 50$[km/h], the time required for cellular communication is 859 seconds, whereas a Piggyback Network can communicate in 161 seconds.

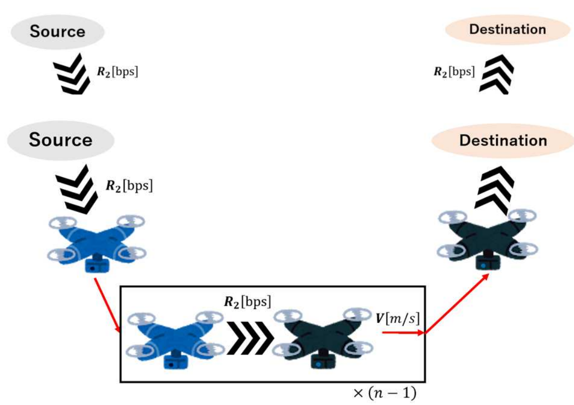

Fig. 2. Data transfer by Piggyback Network with drone-to-drone communication.

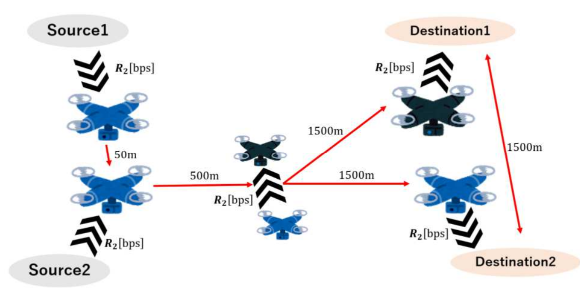

Fig. 3. Piggyback Network and Cellular communications data transfer time.

Fig. 2 shows an example of Piggyback Network communication, including drone-to-drone millimeter wave communication. After the blue drone receives data from the source node, it gets close to the black drone and forwards the transmitted data using the drone-to-drone millimeter-wave communications. The black drone moves and delivers the data to the destination node.

When the number of the forwarding drones from the source to the destination is n, the distance traveled by the drone i is d_i, and the moving speed of all drones is V[m/h], the data delivery time becomes

$$T_3 = \frac{M(1+n)}{R_2} + \frac{1}{V}\sum_{i=1}^{n} d_i\,. \tag{3}$$

As an example, consider the case where data is received from two source nodes as shown in Fig. 3. As before, assume $M = 10$ [GB], $R_1 = 100$ [Mbps], $R_2 = 10$ [Gbps], and $V = 50$[km/h]. When sending data to two destinations with one drone, the time taken is 290 seconds, but when relaying data to a black drone, the communication time is 182 seconds. Therefore, in such cases, piggyback networks, which relay between drones, are superior.

III. Piggyback Network for transmission of Multiple Data

While the previous section discussed Piggyback Network transmitting a single data, this section deals with fulfilling multiple data communication requests as a more general case. First, data transfer time is described, followed by the problem formulation for optimizing the drone's travel path.

A. Multiple Data Transfer Times with Piggyback Network

Fig. 4 shows an example of the Piggyback Network for multiple data delivery from multiple sources and destinations. The drones move to multiple nodes and forward and deliver data. The blue drone receives the data M_1 and M_2 and forwards the M_1 to the black drone. The black drone delivers the data M_1 to the destination node. The end-to-end time to deliver the data M_1 is

$$T_1 = \max\left(\frac{d_1+d_2}{V} + \frac{M_1+M_2}{R_2}, \frac{d_4}{V} + \frac{M_3}{R_2}\right) + \frac{d_5+d_6}{V} + \frac{M_1+M_3}{R_2}, \tag{4}$$

where $d_1, d_2,$ and d_3 are the distance between nodes, V is the speed of all drones, $M_1, M_2,$ and M_3 are the volume of data, and R_2 is the data rate of millimeter wave communication.

From Eq.4, the end-to-end data delivery time depends on the drones' distance traveled and the transmitted data volumes. The distance traveled by each drone depends on the order of visits to the source nodes, destination nodes, and relay points. It also depends on the assignment of end-to-end delivery of one or multiple drones. Therefore, we can minimize the data transfer time of the Piggyback Network by optimizing the

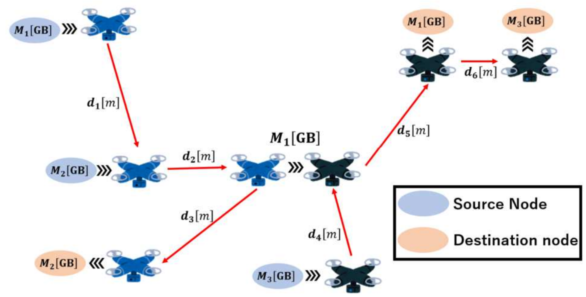

Fig. 4. Data transfer of multiple data by Piggyback Network.

end-to-end communication assignments to the drones and visiting orders of the drones.

B. Problem Formulation

We formulate the problem to optimize mobility routing and data assignments based on the pickup-and-delivery problem, similar to Ref. [5]. The pickup-and-delivery problem is to minimize the delivery cost from the pickup node to the delivery node by optimizing the route of mobilities[8,9]. We extend this problem by adding the delivery of data between mobilities, i.e., communication between drones using millimeter waves.

The optimization problem of assignment of end-to-end data delivery to the drones and visiting order of the drones for the Piggyback Network is formulated as follows:

$$\text{minimize} \sum_{0\le i<N} U_{i+N}, \tag{5}$$

Subject to

$$\sum_{k\in \boldsymbol{K}}\sum_{a\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{A},\boldsymbol{R}} X_{a,b}^{k}=1, \qquad \forall b\in \boldsymbol{S},\boldsymbol{D} \tag{6}$$

$$\sum_{b\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{B},\boldsymbol{R}} X_{2N+k,b}^{k}=1, \qquad \forall k\in \boldsymbol{K} \tag{7}$$

$$\sum_{a\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{A},\boldsymbol{R}} X_{a,b}^{k}=1, \qquad \forall k\in \boldsymbol{K}, b\in \boldsymbol{B} \tag{8}$$

$$\sum_{k\in \boldsymbol{K}}\sum_{a\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{A},\boldsymbol{R}} X_{a,b}^{k}=0, \qquad \forall b\in \boldsymbol{A} \tag{9}$$

$$\sum_{k\in \boldsymbol{K}}\sum_{b\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{B},\boldsymbol{R}} X_{a,b}^{k}=0, \qquad \forall a\in \boldsymbol{B} \tag{10}$$

$$\sum_{a\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{B},\boldsymbol{R}} X_{a,b}^{k} - \sum_{c\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{B},\boldsymbol{R}} X_{a,b}^{k}=0, \ \forall k\in \boldsymbol{K}, b\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{R} \tag{11}$$

$$\sum_{k\in \boldsymbol{K}}\sum_{a\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{A},\boldsymbol{R}} X_{a,b}^{k}\le 2, \qquad \forall b\in \boldsymbol{R} \tag{12}$$

$$\sum_{k\in \boldsymbol{K}}\sum_{a\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{A},\boldsymbol{R}} X_{a,b}^{k}\ne 1, \qquad \forall b\in \boldsymbol{R} \tag{13}$$

$$\sum_{a\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{A},\boldsymbol{R}} X_{a,b}^{k}\le 1, \qquad \forall k\in \boldsymbol{K}, b\in \boldsymbol{R} \tag{14}$$

$$W_{N+i}^{i}=1, \qquad \forall 0\le i<N \tag{15}$$

where $X_{a,b}^{k}$ is binary variable $X_{a,b}^{k}(\in\{0,1\})$, and takes the value 1 when drone k moves to node b from node a, and otherwise 0. N is the number of data transmission requests, and $\boldsymbol{K}$ is the set of drones. $\boldsymbol{S}=\{0,1,\dots,N-1\}$ is the set of source nodes, and $\boldsymbol{D}=\{N,N+1,\dots,2N-1\}$ is the set of destination node. Node $i(\in \boldsymbol{S})$ has the data addressed to node $i+N(\in \boldsymbol{D})$. $\boldsymbol{A}=\{2N,2N+1,\dots,2N+|\boldsymbol{K}|-1\}$ is the set of initial position node, and drone k starts from node $2N+k$. $B=\{2N+|\boldsymbol{K}|\}$ is the virtual end position of the drone operation, when $X_{a,2N+|\boldsymbol{K}|}^{k}=1$, drone k completes all operations. $R=\{2N+|\boldsymbol{K}|+1,\dots\}$ is the set of relay node, and drone k and k' relay at $R_{k,k'}(\in \boldsymbol{R})$.

U_a is the time at which the drone departed node a, and is calculated as follows:

$$U_a=\max_{k\in \boldsymbol{K},b\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{A},\boldsymbol{R}}\left[X_{b,a}^{k}\left(U_b+\frac{d_{b,a}}{V}+\frac{M_a}{R_2}\right)\right],$$
$$\forall a\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{B},\boldsymbol{R} \tag{16}$$

$$U_a=0, \qquad a\in \boldsymbol{A} \tag{17}$$

where V is the speed of drones, and M_a is amount of data communicated at node a. $d_{a,b}$ is distance between node a and b. It is obtained from the x and y coordinates C_a^x and C_a^y of each node. The coordinates of the relay node R are obtained from the following equation.

$$\left[C_{R_{k,k'}}^{x}, C_{R_{k,k'}}^{y}\right] = \left[\frac{1}{2}\sum_{b}\left[C_b^x\left(X_{b,a}^{k}+X_{b,a}^{k'}\right)\right], \frac{1}{2}\sum_{b}\left[C_b^y\left(X_{b,a}^{k}+X_{b,a}^{k'}\right)\right]\right] \tag{18}$$

W_a^i is a value that is 1 if data i reaches node a and 0 otherwise, and is calculated as follows:

$$W_a^i=\max_{k\in \boldsymbol{K},b\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{A},\boldsymbol{R}}\left(X_{b,a}^{k}W_b^i\right), \ \forall 0\le i<N, a\in \boldsymbol{S},\boldsymbol{D},\boldsymbol{B},\boldsymbol{R} \tag{19}$$

$$W_a^i=\begin{cases}1 & \text{if } a=i\\ 0 & \text{otherwise}\end{cases}. \quad \forall 0\le i<N, a\in \boldsymbol{A} \tag{20}$$

The objective function (5) minimizes the total time to complete data transfer. The constraint (6) indicates that all source and destination nodes are visited once. Eqs. (7), (8), (9), and (10) are constraints on the initial and end points of the drone. The constraint (11) indicates that the source, destination, and relay nodes are visited and departed by the same drone. The constraints (12), (13), and (14) indicate that the relay node is visited once by two drones or is not used. Eq. (15) is a constraint that guarantees that data will be sent from the source node to the destination node.

IV. Simulation Evaluation

In this section, we evaluate the throughput of a Piggyback Network that takes into account drone-to-drone millimeter wave communication. First, the environment assumed in the simulations is described, followed by a description of the simulation results.

A. Simulation Environment

We solve the optimization problem formulated in the previous section using the GUROBI optimizer with Python and evaluate the performance of the Piggyback network that includes drone-to-drone communication links.

It is assumed that there are four source and four destination nodes on the Euclidean plane, and the drone can

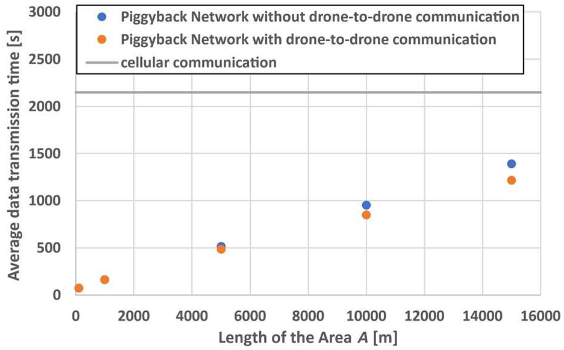

Fig. 5. The relationship between size of Euclidean plane and data transmission time
($M = 25$ [GB], $V = 70$[km/h], $R_2 = 10$[Gbps])

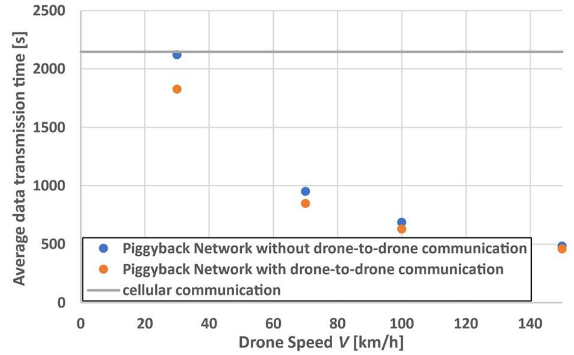

Fig. 7. The relationship between speed of drone and data transmission time
($A = 10000$ [m], $M = 25$[GB], $R_2 = 10$[Gbps])

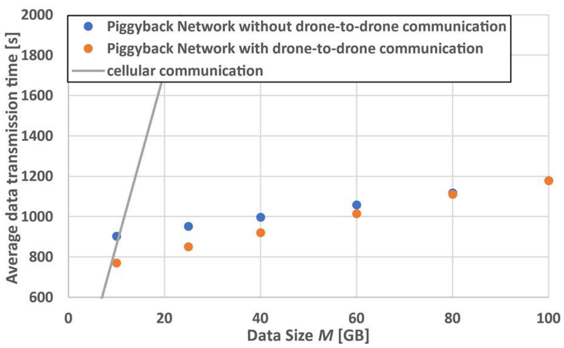

Fig. 6. The relationship between data size and data transmission time
($A = 10000$ [m], $V = 70$[km/h], $R_2 = 10$[Gbps])

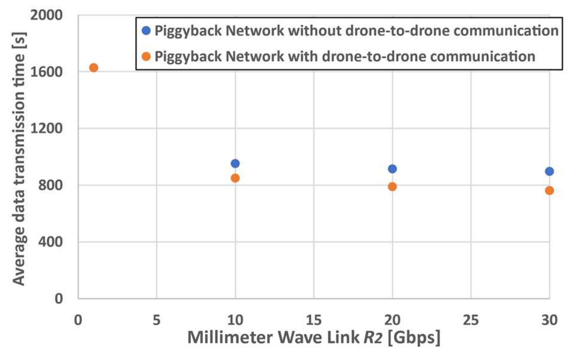

Fig. 8. The relationship between data rate of millimeter wave and data transmission time
($A = 10000$ [m], $M = 25$[GB], $V = 70$[km/h])

move freely on the plane. The drones use the wireless communication of the IEEE 802.15.3e standard and follow the "Stop/Slow-down & Go" policy described in [4], stopping and communicating at the same coordinates. For the comparison, we introduce the Piggyback Network without the drone-to-drone relay proposed that has been proposed in [5].

B. Simulation Result

In this simulation, the Euclidean place is an $A \times A$ square, the size of the data to be transmitted is M, the data rate of millimeter wave communication is R, and the speed of drones are V.

Fig. 5 shows the relationship between the size of the Euclidean plane and data transmission time. The longest data transmission time under these conditions is 1392 seconds. Since it takes 2147 seconds to transmit 25GB of data by cellular transmission at 100Mbps, it can be said that the Piggyback Network transmits data faster than cellular transmission. We can also see that the Piggyback network that takes into account drone-to-drone communication can transfer data faster than the normal Piggyback Network when the size of the area exceeds a certain value. This means that data transfer was efficiently performed by relaying data between drones. As the area size increases, the value of distance d_i in (3) increases. This also increases the path length shortened by relaying between drones, which reduces the communication time more than Piggyback networks without drone-to-drone communication.

Fig. 6 shows the relationship between the size of data and data transmission time. We can see that the Piggyback network, including the drone-to-drone millimeter wave communications, is effective in the interval between 20 GB and 60 GB data size, although cellular communications are faster when the data is small. In [5], the Piggyback Network only outperforms conventional communication systems when the data size is large, but the present simulation shows that communication speed can be improved even when transporting data of about 10 GB by using data relays between drones.

Fig. 7 shows the relationship between the speed of drones and data transmission time. The figure shows that as the speed of the drone decreases, the data transfer time by the Piggyback Network increases. It can also be seen that even when drone speeds are low, the piggyback network communication times are improved to some extent by relaying between drones.

Fig. 8 shows the relationship between the data rate of millimeter wave and data transmission time. We can see that the impact of R_2 data rate increase on the Piggyback Network is very small above 10Gbps. On the other hand, we can also see that a larger data rate will again have an impact on the relay between drones. This is the result of the reduced time for relaying, which results in the selection of data transfer between drones for more efficient visits.

V. Conclusion

We have proposed an optimization scheme for the Piggyback Network, including the drone-to-drone millimeter wave communications that transfer data between multiple source and destination nodes. This optimization problem requires determining the assignment of multiple source-to-destination data delivery requirements to the drones and the communication paths of each drone from the sources to the destinations by moving and forwarding using millimeter wave communications. In this paper, we formulated the optimization problem to minimize the end-to-end data transfer time. We solved the problem using the GUROBI optimizer and performed a simulation comparison with the Piggyback Network without drone-to-drone millimeter wave communications. The results of the simulation comparisons confirm that the Piggyback Network proposed in this paper, including drone-to-drone millimeter wave communications, performs better than the conventional method.

Our future works include consideration of the impact of increasing the number of drones on communication speed, the impact of the environment in which communication takes place on millimeter waves, and the cost of introducing drones. In addition, it also includes developing efficient heuristic algorithms that can be applied to large-scale Piggyback Networks with more source nodes, destination nodes, and drones. Optimization taking into account the quality of the millimeter wave links that have been modeled in [7] for drone-to-drone communication will also be an important study for realizing the proposed optimization approach.

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