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PAPER

On the Optimality of Forest-Type File Transfers on a File Transmission Net

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SUMMARY A problem of obtaining an optimal file transfer on a file transmission net N is to consider how to transmit, with a minimum total cost, copies of a certain file of information from some vertices to others on N by the respective vertices' copy demand numbers. This problem is NP-hard for a general file transmission net. So far, some class of N on which polynomial time algorithms for obtaining an optimal file transfer are designed has been known. In addition, if we deal with restricted file transfers, i.e., forest-type file transfers, we can obtain an optimal 'forest-type' file transfer on more general class of N. This paper proves that for such general nets it suffices to consider forest-type file transfers in order to obtain an optimal file transfer.

key words: *file transfer, optimality, minimum cost, forest-type*

1. Introduction

As a model of file distribution of direct mail type, it is useful for us to consider a problem of transmitting copies of a certain file of information with a minimum total cost. In this model, we assume that everywhere we can duplicate copies of the file as well as we can transmit and take out them. A file transmission net N is such a file distribution model from some vertices to others by the respective vertices' copy demand numbers, where a cost of file duplication at vertex and a cost of file transmission along arc are defined. The numbers of file copies duplicated at vertices as well as the numbers of file copies transmitted along arcs which achieve the minimum total cost file distribution are a solution to the problem, which is called an optimal file transfer on N. This problem is NP-hard for a general file transmission net [1]. A polynomial time algorithm for obtaining an optimal file transfer on N with a single source vertex has been known so far [2]. In addition, if we deal with restricted file transfers, i.e., forest-type file transfers, we can obtain an optimal file transfer on N with one or more source vertices [3].

This file transfer problem is quite different from data transfer problem [4] and scheduling file transfer problem [5] because the latter problems deal with time. Some similar problems are known such as file allocation problem [6] and file assignment problem [7]. However, these problems are conceptually different from our file transfer problem, when making copies at any vertex is considered so as to minimize the total cost.

This paper proves that for N with one or more source vertices it suffices to consider forest-type file transfers in order to obtain an optimal file transfer. This implies from [3] that we can obtain an optimal file transfer on such N in polynomial time.

In the rest of the paper, we proceed as follows. In Sect. 2, we give preliminaries for this paper. In Sect. 3, we define the superimposition net and show relationship between such net and file transfer. In Sect. 4, we show the optimality of 'forest-type' file transfers. Finally, we mention concluding remark and future tasks.

2. Preliminaries

In this section, we define some terms in order to formulate a problem of obtaining an optimal file transfer on a file transmission net. In relation to basic terminologies such as vertex, arc, path, circuit, tree, forest, underlying graph and so forth, on graph theory, refer to those in [8]. Let $\mathbb{Z}$ and $\mathbb{Z}^+$ denote the set of all integers and that of all positive integers, respectively, and let $\mathbb{Z}_0^+ = \mathbb{Z}^+ \cup \{0\}$. In the following unless otherwise stated, an arc, a path, a circuit and a graph indicate a directed arc, a directed path, a directed circuit and a directed graph, respectively. A graph G with a vertex set V and an arc set B is denoted by $G = (V, B)$. For a vertex v, $B_+(v)$ and $B_-(v)$ are the sets of all arcs whose tail and head is v, respectively, and $|B_+(v)|$ and $|B_-(v)|$ is called the outdegree and indegree of v, respectively. A vertex w is called a leaf if $B_+(w) = \phi$. For two distinct vertices u and w, a path from u to w, or we simply say a u-w path, is a path which begins at u and ends at w. If G contains a u-w path, we say w is reachable from u. If a vertex on a circuit L is reachable to a vertex v, we say L is reachable to v. The sets of arcs and vertices on a path P is denoted by $B(P)$ and $V(P)$, respectively and the vertex at which P begins and ends is denoted by $s(P)$ and $t(P)$, respectively. For two vertices u and w on a path P, if a u-w path P' satisfies $V(P') \subseteq V(P)$ and $B(P') \subseteq B(P)$, we say P' is a u-w subpath of P.

We consider a model of directed communication nets, called a file transmission net N, denoted by $N = (V, B, s_V, c_V, d, c_B)$, where (V, B) is a finite connected directed graph with neither selfloops nor paral-

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lel arcs such that (1) with each vertex $v \in V$, three parameters $s_V(v)$, $c_V(v)$ and $d(v)$ are associated and (2) with each arc $e \in B$, one parameter $c_B(e)$ is associated. These parameters $s_V(v)$, $c_V(v)$, $d(v)$ and $c_B(e)$ are called the original number, the copying cost and the copy demand, respectively, of vertex v, and the transmission cost of arc e. Let s_V, c_V, d and c_B satisfy s_V: $V \to \{0, 1\}$, c_V: $V \to \mathbb{Z}^+$, d: $V \to \mathbb{Z}_0^+$ and c_B: $B \to \mathbb{Z}^+$. Suppose that N satisfies $(w, u) \in B$ and $c_B((w, u)) = c_B((u, w))$ if $(u, w) \in B$.

Suppose that (1) some information to be transmitted through the inside of N has been written in a file, (2) the written file is denoted by J, where the file means an abstract concept of information carrier and (3) vertices u such that $s_V(u) = 1$, to each of which one copy of J is first given from the outside of N, are called source vertices. The set of all source vertices is denoted by S, and let $S \neq \phi$. Suppose that at any vertex in V, we can easily duplicate J and we do not matter the difference from copies of J. In this situation, $c_V(v)$ means the duplication cost per one copy of J at a vertex v, $d(v)$ means the number of copies of J needed at v, and $c_B(e)$ means the transmission cost per one copy of J along an arc e. Suppose that these costs c_V and c_B are all linear. Let $U = \{u \in V | \, d(u) > 0\}$. In the following, by N we mean such a file transmission net $N = (V, B, s_V, c_V, d, c_B)$.

For a path P, let $c_B(P) = \sum_{e \in B(P)} c_B(e)$. For two distinct vertices u and w, if a u-w path P satisfies $c_B(P) \leq c_B(P')$ among all u-w paths P', then we say P is a minimum cost u-w path, whose cost is denoted by $c_{u,w}$. For each vertex v in V, let $c_{v,v} = 0$. For a mapping f on B, if every arc e on a path P satisfies $f(e) > 0$, then we say P is f-connected. Those copies of J given to every source vertex are duplicated, if necessary, and distributed to vertices v in such a way that $d(v)$ copies of J are taken out from v to the outside of N based on a file transfer defined below.

Definition 1: In N, let ψ and f satisfy ψ: $V \to \mathbb{Z}_0^+$ and f: $B \to \mathbb{Z}_0^+$. Then (ψ, f) is called a file transfer on N if ψ and f satisfies the following two conditions:
(C1) The conservation of the number of J on vertex; for any vertex v in V there holds

$$s_V(v) + \psi(v) + \sum_{e \in B_-(v)} f(e) = \sum_{e \in B_+(v)} f(e) + d(v).$$

(C2) The availability of J; for any vertex v such that $\psi(v) > 0$, there exists an f-connected path from some source vertex to v.

For a file transfer $D = (\psi, f)$ on N, let

$$C(D) = \sum_{v \in V} c_V(v) \cdot \psi(v) + \sum_{e \in B} c_B(e) \cdot f(e),$$

which is called the cost of D. A file transfer with minimum cost is said to be optimal. □

In a file transfer (ψ, f), $\psi(v)$ means the number of copies of J made at a vertex v and $f(e)$ means the number of copies of J transmitted along an arc e.

A subset M of V is defined by c_V and c_B, which is very important to obtain an optimal file transfer.

Definition 2: In N, let M be the set of all vertices m such that $c_V(m) < c_V(x) + c_{x,m}$ for any vertex x in $V \backslash \{m\}$. For each vertex v in V, let $H(v) = \{w \in V | \, w$ satisfies $c_V(w) + c_{w,v} \leq c_V(x) + c_{x,v}$ for any vertex x in $V.\}$. □

In relation to H and M, the following proposition holds.

Proposition 1[2]: In N, each vertex $v \in V$ satisfies $H(v) \cap M \neq \psi$. Besides there holds $H(m) = \{m\}$ if and only if $m \in M$. □

In the following unless otherwise stated, let the function h on V satisfy $h(v) \in H(v) \cap M$ for a vertex v. That is, $h(v)$ is one of the best vertices at which we make and transmit copies for v.

Since, in general, the problem of obtaining an optimal file transfer has been proven NP-hard [1], some conditions might be necessary in order to solve the problem in polynomial time [9]. Thus, in this paper let N satisfy $M \cup S \subseteq U$, which is a sufficient condition to solve the problem in polynomial time for N with $S = \{u\}$ and $s_V(u) = 1$ [2].

3. A File Transfer and Its Identical Superimposition Net

3.1 Properties of File Transfer

In this subsection, we show some properties of a file transfer.

Lemma 1: For any vertex y satisfying $\sum_{e \in B_-(y)} f(e) \geq 1$, every file transfer (ψ, f) on N contains an f-connected path to such y from a vertex m satisfying $\psi(m) > 0$.

Proof: By s_V: $V \to \{0, 1\}$, $S \subseteq U$ and (C1), we have

$$\psi(v) + \sum_{e \in B_-(v)} f(e) \geq \sum_{e \in B_+(v)} f(e) \quad (v \in V).$$

Clearly, for the above y, there exists an arc $e = (x, y)$ satisfying $f(e) > 0$. If $\psi(x) > 0$, then the lemma holds. Otherwise, by $\sum_{e \in B_+(x)} f(e) \geq 1$ and the above inequality, we have another arc $e' = (x', x)$ satisfying $f(e') > 0$. Since N is finite, we have this lemma. □

The next lemma is an expansion of Lemma1 of [2].

Lemma 2: For any vertex u in $U \backslash S$, every file transfer (ψ, f) on N contains an f-connected path from some source vertex to u.

Proof: If a vertex u in $U \backslash S$ satisfies $\psi(u) > 0$, we have this lemma from (C2). Otherwise we can see from (C1) and f: $B \rightarrow \mathbb{Z}_0^+$ that

$$\sum_{e \in B_-(u)} f(e) = \sum_{e \in B_+(u)} f(e) + d(u) \geq d(u) \geq 1,$$

which implies from Lemma 1 that (ψ, f) contains an f-connected path to u from a vertex m satisfying $\psi(m) > 0$. Therefore, we can see from (C2) that (ψ, f) contains an f-connected path from some source vertex to u via m. Hence, we have this lemma. □

The following proposition is very useful to obtain an optimal file transfer.

Proposition 2: Let a file transfer $D = (\psi, f)$ on N satisfy $\psi(u) > 0$ for a vertex u in $V \backslash M$. Then, there exists on N another file transfer $D'' = (\psi'', f'')$ such that $C(D) \geq C(D'')$ and $\psi''(v) = 0$ for any vertex v in $V \backslash M$.

Proof: In this proof, let $V(D) = \{v \in V \backslash M | \psi(v) > 0\}$ for any file transfer $D = (\psi, f)$. In order to prove this proposition, we have only to show that for a file transfer D such that $V(D) \neq \psi$, there exists another file transfer D' such that (1) $C(D) \geq C(D')$, and (2) $V(D) \supset V(D')$.

Let $u \in V(D)$. We have $h(u) \neq u$ from $u \notin M$ and $h(u) \in M$. Let P be a minimum cost $h(u)$-u path. For ψ and f, functions ψ' on V and f' on B are defined to be

$$\begin{aligned} &\psi'(h(u)) = \psi(h(u)) + \psi(u), \quad \psi'(u) = 0, \\ &\psi'(v) = \psi(v) \quad (v \in V \backslash \{h(u), u\}), \\ &f'(e) = f(e) + \psi(u) \quad (e \in B(P)), \\ &f'(e) = f(e) \quad (e \in B \backslash B(P)). \end{aligned} \tag{1}$$

Then, obviously, ψ' and f' satisfies (C1) as well as ψ': $V \rightarrow \mathbb{Z}_0^+$ and f': $B \rightarrow \mathbb{Z}_0^+$. We can see from $h(u) \in M \subseteq U$ and Lemma 2 that (ψ, f) contains an f-connected path from some source vertex to $h(u)$.

Therefore, ψ' and f' satisfies (C2) because $f'(e) \geq f(e)$ for any arc $e \in B$. Thus, $D' = (\psi', f')$ is a file transfer on N. Moreover, it follows from Eq. (1) that $V(D') = V(D) \backslash \{u\} \subset V(D)$. Finally, from $\psi(u) > 0$ and $h(u) \in H(u)$ we have

$$\begin{aligned} &C(D') - C(D) \\ &\quad = \{c_V(h(u)) + c_{h(u),u} - c_V(u)\} \cdot \psi(u) \leq 0. \end{aligned}$$

Hence we have this proposition. □

It turns out from Proposition 2 that, in order to obtain an optimal file transfer, we have only to consider file transfers such that all vertices where copies of J are made belong to M. Therefore, in the following we deal with a file transfer (ψ, f) satisfying

Property (ψ_1): If $\psi(v) > 0$, then $v \in M$.

3.2 The Superimposition Net of Paths

In the following, a net of N, denoted by $N(\alpha, \beta)$, means a network whose structure is identical to that of N and with each vertex v and each arc e, $\alpha(v)$ and $\beta(e)$ associated, respectively. Note that file transfer itself is a net of N. In the following, every path set (or circuit set) may contain some paths (or circuits) more than once. The superimposition net is obtained from such path and/or circuit sets as follows.

Definition 3: For a path set $\mathbb{P}$ and a circuit set $\mathbb{L}$ on N, the superimposition net $N(\alpha, \beta)$, denoted by $N(\mathbb{P} \cup \mathbb{L})$, is defined to be

(N1) The vertex set and the arc set is V and B, respectively.
(N2) The weight $\alpha(v)$ of each vertex v is the number of paths on $\mathbb{P}$ which begins at v minus that of paths on $\mathbb{P}$ which ends at v. If $\mathbb{P}$ has no path which begins or ends at v, then let $\alpha(v) = 0$.
(N3) The weight $\beta(e)$ of each arc e is the total number of paths and circuits on $\mathbb{P} \cup \mathbb{L}$ that contains e. If $\mathbb{P} \cup \mathbb{L}$ has no path or circuit containing e, then let $\beta(e) = 0$. □

Note that in Definition 3, we can have the superimposition nets $N(\mathbb{P})$ and $N(\mathbb{L})$ if we let $\mathbb{L} = \phi$ and $\mathbb{P} = \phi$, respectively. Thus, in the following, when we deal with $N(\mathbb{P} \cup \mathbb{L})$, it may happen that $\mathbb{P} = \phi$ or $\mathbb{L} = \phi$.

Note that $N(\mathbb{P} \cup \mathbb{L}) = N(\alpha, \beta)$ satisfies α: $V \rightarrow \mathbb{Z}$ and β: $B \rightarrow \mathbb{Z}_0^+$ from Definition 3.

Definition 4: Let $N(\alpha_1, \beta_1)$ and $N(\alpha_2, \beta_2)$ be nets of N. Another net of N, denoted by $N(\alpha_3, \beta_3)$, is a network whose structure is (V, B) and functions α_3 on V and β_3 on B are defined to be

$$\alpha_3(v) = \alpha_1(v) + \alpha_2(v) \quad (v \in V),$$

$$\beta_3(e) = \beta_1(e) + \beta_2(e) \quad (e \in B),$$

which is called the sum of $N(\alpha_1, \beta_1)$ and $N(\alpha_2, \beta_2)$. □

Also, for the above superimposition nets, we can define their sum.

For a path set $\mathbb{P}$ and a circuit set $\mathbb{L}$, $\mathbb{P}$ and $\mathbb{L}$ is called disjoint if any path $P \in \mathbb{P}$ and any circuit $L \in \mathbb{L}$ satisfies $V(P) \cap V(L) = \phi$. Let $x \in V(P) \cap V(L)$ for P in a path set $\mathbb{P}$ and L in a circuit set $\mathbb{L}$. Let an $s(P)$-$t(P)$ path P' consist of P and L via x, i.e., the $s(P)$-x subpath of P, L, and the x-$t(P)$ subpath of P. Then, for $\mathbb{P}$ and $\mathbb{L}$, let a path set $\mathbb{P}'$ and a circuit set $\mathbb{L}'$ be $\mathbb{P}' = \mathbb{P} \backslash \{P\} \cup \{P'\}$ and $\mathbb{L}' = \mathbb{L} \backslash \{L\}$. After repeating this operation of getting $\mathbb{P}'$ and $\mathbb{L}'$ from such $\mathbb{P}$ and $\mathbb{L}$, we have a path set $\mathbb{P}''$ and a circuit set $\mathbb{L}''$ such that $\mathbb{P}''$ and $\mathbb{L}''$ is disjoint or $\mathbb{L}'' = \phi$. By Definition 4, $N(\mathbb{P}'' \cup \mathbb{L}'')$ is identical to $N(\mathbb{P} \cup \mathbb{L})$. In the following,

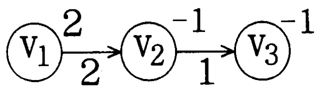

Fig. 1 An example of nets $N_1(\alpha_1, \beta_1)$.

when we deal with $N(\mathbb{P} \cup \mathbb{L})$, we assume that the path set $\mathbb{P}$ and the circuit set $\mathbb{L}$ is disjoint or $\mathbb{L} = \phi$.

In relation to the above definition, we have the next trivial lemma.

Lemma 3: For a path set $\mathbb{P}$ and a circuit set $\mathbb{L}$ on N, let $N(\alpha, \beta) = N(\mathbb{P} \cup \mathbb{L})$. Then, we have

$$\begin{aligned}\sum_{v \in V} c_V(v) \cdot \alpha(v) + \sum_{e \in B} c_B(e) \cdot \beta(e) \\ = \sum_{P \in \mathbb{P}} \{c_V(s(P)) + c_B(P) - c_V(t(P))\} \\ + \sum_{L \in \mathbb{L}} c_B(L). \qquad (2)\end{aligned}$$

□

Note that the above $N(\alpha, \beta)$ is just a net of N, not always a file transfer.

Here is an example. A net $N_1(\alpha_1, \beta_1)$ is shown in Fig. 1, where the value near vertex v and arc e denotes $\alpha_1(v)$ and $\beta_1(e)$, respectively. Let P_1 be the v_1-v_2 path and let P_2 be the v_2-v_3 path. Clearly, $N_1(\alpha_1, \beta_1)$ is identical to $N_1(\{P_1, P_1, P_2\})$. In addition, we have

$$\begin{aligned}&\sum_{v \in V} c_V(v) \cdot \alpha_1(v) + \sum c_B(e) \cdot \beta_1(e) \\ &= 2c_V(v_1) - c_V(v_2) - c_V(v_3) + 2c_B(v_1, v_2) \\ &\quad + c_B(v_2, v_3) \\ &= 2\{c_V(v_1) + c_B(v_1, v_2) - c_V(v_2)\} \\ &\quad + \{c_V(v_2) + c_B(v_2, v_3) - c_V(v_3)\} \\ &= \sum_{P \in \{P_1, P_1, P_2\}} \{c_V(s(P)) + c_B(P) - c_V(t(P))\}.\end{aligned}$$

A function whose image has other than zero is called a nonnull function. In relation to the superimposition net of circuit sets, we have the next trivial lemma.

Lemma 4: If a nonnull function β: $B \to \mathbb{Z}_0^+$ satisfies

$$\sum_{e \in B_-(v)} \beta(e) = \sum_{e \in B_+(v)} \beta(e) \quad (v \in V),$$

then there exists a circuit set $\mathbb{L}$ such that $N(\mathbb{L})$ is identical to $N(\alpha, \beta)$ with α: $V \to \{0\}$. □

In relation to the above, we have the following lemma.

Lemma 5: Suppose that nonnull functions α: $V \to \mathbb{Z}$ and β: $B \to \mathbb{Z}_0^+$ on N satisfy

(C3) $\alpha(v) + \sum_{e \in B_-(v)} \beta(e) = \sum_{e \in B_+(v)} \beta(e) \quad (v \in V)$.

Let $V_1 = \{v \in V \,|\, \alpha(v) > 0\}$ and $V_2 = \{v \in V \,|\, \alpha(v) < 0\}$. Then, we have a path set $\mathbb{P}$ satisfying.

(P0) For a circuit set $\mathbb{L}$, $N(\mathbb{P} \cup \mathbb{L})$ is identical to $N(\alpha, \beta)$ and each path P in $\mathbb{P}$ satisfies $s(P) \in V_1$ and $t(P) \in V_2$.

Proof: Let $u_1 \in V_1$. It follows from (C3) that $N(\alpha, \beta)$ contains a β-connected path which begins at u_1 as well as ends at a vertex in V_2 because $N(\alpha, \beta)$ is finite. Let P be such a path and let $u_2 = t(P)$. For α, β and P, functions α' on V and β' on B are defined to be

$$\begin{aligned}&\alpha'(u_1) = \alpha(u_1) - 1, \\ &\alpha'(u_2) = \alpha(u_2) + 1, \\ &\alpha'(v) = \alpha(v) \quad (v \in V \backslash \{u_1, u_2\}), \\ &\beta'(e) = \beta(e) - 1 \quad (e \in B(P)), \\ &\beta'(e) = \beta(e) \quad (e \in B \backslash B(P)). \qquad (3)\end{aligned}$$

Then, it is clear that α' and β' satisfies

$$\alpha'(v) + \sum_{e \in B_-(v)} \beta'(e) = \sum_{e \in B_+(v)} \beta'(e) \quad (v \in V).$$

Here, let $V_1' = \{v \in V | \alpha'(v) > 0\}$ and $V_2' = \{v \in V | \alpha'(v) < 0\}$. Then, it follows from Eq. (3) that $V_1' \subseteq V_1$ and $V_2' \subseteq V_2$. If $V_1' = \phi$, then α': $V \to \{0\}$ and $\sum_{e \in B_-(v)} \beta'(e) = \sum_{e \in B_+(v)} \beta'(e)$, which implies from Lemma 4 that this lemma holds as $\mathbb{P} = \{P\}$ and $L = \phi$. Otherwise, for $N(\alpha', \beta')$, we repeat the operation of getting P from $N(\alpha, \beta)$. Since it follows from Eq. (3) that

$$\sum_{v \in V_1'} \alpha'(v) = \sum_{v \in V_1} \alpha(v) - 1 < \sum_{v \in V_1} \alpha(v),$$

we finally have a path set $\mathbb{P}$ and a circuit set $\mathbb{L}$ satisfying (P0) from Lemma 4, after repeating such operations $\sum_{v \in V_1} \alpha(v)$ times. □

3.3 A File Transfer Based on Superimposing Path Sets

Here, we show that any file transfer is identical to the superimposition net of path and/or circuit sets.

Lemma 6: For a file transfer (ψ, f) on N such that $M \cup S \subseteq U$ and $M \backslash S \neq \phi$, let a function α on V satisfy

$$\alpha(v) = s_V(v) + \psi(v) - d(v) \quad (v \in V). \qquad (4)$$

Then, we have a path set $\mathbb{P}$ satisfying

(P1) For a circuit set $\mathbb{L}$, $N(\mathbb{P} \cup \mathbb{L})$ is identical to $N(\alpha, f)$, and each path P in $\mathbb{P}$ satisfies $s(P) \in S \cup M$ and $t(P) \in U$.

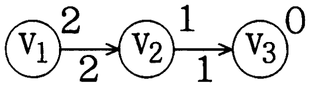

Fig. 2 A file transfer $(\psi_2,\ f_2)$ on N_2.

(P2) For each m in $M\backslash S$, $\mathbb{P}$ has at least one path which ends at m.

Proof: By (C1) and Eq. (4) we have

$$\alpha(v)+\sum_{e\in B_-(v)} f(e)=\sum_{e\in B_+(v)} f(e) \quad (v\in V).$$

Let $V_1=\{v\in V|\, s_V(v)+\psi(v)>d(v)\}$ and $V_2 = \{v\in V|s_V(v)+\psi(v)<d(v)\}$. Then, it follows from (ψ_1) that $V_1\subseteq S\cup M$. Obviously, there holds $V_2\subseteq U$. Therefore, it follows from (P0) of Lemma 5 that there exists a path set $\mathbb{P}$ such that $N(\mathbb{P}\cup\mathbb{L})$ is identical to $N(\alpha,\ f)$ for a circuit set $\mathbb{L}$ and each path $P\in\mathbb{P}$ satisfies $s(P)\in S\cup M$ and $t(P)\in U$. Since $\mathbb{P}$ and $\mathbb{L}$ is disjoint, if $\mathbb{P}$ contains no path which ends at $m\in M\backslash S$, then from Lemma 2 we have a path P in $\mathbb{P}$ passing m because $N(\mathbb{P}\cup\mathbb{L})$ is identical to $N(\alpha,\ f)$. Let P_1 and P_2 be $s(P)$-m and m-$t(P)$ subpaths, respectively, of this P and let $\mathbb{P}'=\mathbb{P}\cup\{P_1,P_2\}\backslash\{P\}$. Then, $N(\mathbb{P}'\cup\mathbb{L})$ is identical to $N(\mathbb{P}\cup\mathbb{L})$. In addition, we have $s(P_2)=m\in M\backslash S\subseteq M\cup S$ and $t(P_1)=m\in M\backslash S\subseteq U$, which implies that $s(P')\in M\cup S$ and $t(P')\in U$ for each path $P'\in\mathbb{P}'$. As far as the obtained $\mathbb{P}'$ has no path which ends at a vertex in $M\backslash S$, repeat the above operation. Consequently, we obtain a path set satisfying (P1) and (P2). Hence we have this lemma. □

A file transfer $(\psi_2,\ f_2)$ is shown in Fig. 2, on N_2 such that $S=\{v_1\}$, $s_V(v_1)=1$, $d(v_1)=1$, $d(v_2)=2$, $d(v_3)=1$ and $M=\{v_1,v_2,v_3\}$. The value near vertex v and arc e denotes $\psi_2(v)$ and $f_2(e)$, respectively. From Eq. (4), we have $\alpha(v_1)=2$, $\alpha(v_2)=-1$, and $\alpha(v_3)=-1$, which is identical to the net of Fig. 1. Therefore, for v_1-v_2 path P_1 and v_2-v_3 path P_2, it turns out that the path set $\{P_1,P_1,P_2\}$ satisfies (P1) and (P2) for $\mathbb{L}=\phi$.

Note that it may happen that a path set satisfying (P1) has no path which begins at some source vertex u, e.g. if $\alpha(u)<0$.

Definition 5: Let $s_0\notin V$. For a path set $\mathbb{P}$, let $G(\mathbb{P})$ denote a directed graph with vertex set $\{s_0\}\cup\{s(P),t(P)|\ P\in\mathbb{P}\}$ and arc set $\{(s_0,u)|\ u\in S\}\cup\{(s(P),t(P))|\ P\in\mathbb{P}\}$. In addition, let $R(\mathbb{P})=\{v\in V|\ G(\mathbb{P})$ contains an s_0-v path $\}$. □

Note that $\{s_0\}\cup S\subseteq R(\mathbb{P})$ for any path set $\mathbb{P}$.

The next definition, used in the following lemma, deals with relationship between two paths.

Definition 6: For a path P_1 and a path P_2, let $x\in V(P_1)\cap V(P_2)$. Let ${P_1}'$ consist of $s(P_1)$-x subpath of P_1 and x-$t(P_2)$ subpath of P_2 and let ${P_2}'$ consist of $s(P_2)$-x subpath of P_2 and x-$t(P_1)$ subpath of P_1. We call ${P_1}'$ and ${P_2}'$ exchange paths of P_1 and P_2 by x. In addition, if a path P_3 denoted by $V(P_3)=\{u_1,u_2,\cdots,u_p\}$ and $B(P_3)=\{(u_i,u_{i+1})|\ 1\le i\le p-1\}$ satisfies for a path P_4

$$u_a,u_b\in V(P_3)\cap V(P_4)\quad (a<b),$$

$$u_i\in V(P_4)\quad (1\le i<a, b<i\le p),$$

then P_3 and P_4 is said to be maximally adjacent between u_a and u_b. □

Lemma 7: For a file transfer $(\psi,\ f)$ on N such that $M\cup S\subseteq U$ and $M\backslash S\neq\phi$, let a function α on V satisfy Eq. (4). For a path set $\mathbb{P}$ satisfying (P1), let its subset $\mathbb{P}_1$ satisfy (P2) and $M\backslash R(\mathbb{P}_1)\neq\phi$. Then, we have a path set $\mathbb{P}'$ satisfying (P1), whose subset $\mathbb{P}''$ satisfies (P2) and $R(\mathbb{P}_1)\subset R(\mathbb{P}'')$.

Proof: At first, we consider the above $\mathbb{P}$ and $\mathbb{P}_1$. Note that Lemma 6 says there exist such path sets $\mathbb{P}$ and $\mathbb{P}_1$. Let $m\in M\backslash R(\mathbb{P}_1)$ and let P be a path of $\mathbb{P}_1$ which ends at m. Then, by (P1) we have $s(P)\in S\cup M$. Since $m\notin R(\mathbb{P}_1)$ and $P\in\mathbb{P}_1$, there holds $s(P)\in M\backslash R(\mathbb{P}_1)$. Similarly, the path in $\mathbb{P}_1$ which ends at $s(P)$ begins at a vertex in $M\backslash R(\mathbb{P}_1)$. Therefore, since $G(\mathbb{P}_1)$ is finite, we have

(P2′) For each vertex $m'\in M\backslash R(\mathbb{P}_1)$, $G(\mathbb{P}_1)$ contains a circuit with vertices only in $M\backslash R(\mathbb{P}_1)$ which is reachable to m'.

Each vertex $r\in R(\mathbb{P}_1)\backslash(\{s_0\}\cup S)$ satisfies $r\in M\backslash S$. Since $\mathbb{P}_1$ satisfies (P2), the path in $\mathbb{P}_1$ which ends at r begins at a vertex in $R(\mathbb{P}_1)$. Therefore, since $G(\mathbb{P}_1)$ is finite, we have

(P2″) $G(\mathbb{P}_1)$ has no path from a vertex in $M\backslash R(\mathbb{P}_1)$ to a vertex in $R(\mathbb{P}_1)$.

In the following let $\mathbb{P}^1=\mathbb{P}$. For a vertex $m\in M\backslash S$, we can see from $M\subseteq U$ and Lemma 2 that $N(\alpha,\ f)$ contains an f-connected path from some source vertex to m. Therefore, by (P2′) $N(\alpha,\ f)$ contains a path P^1 from a vertex $m_1'\in R(\mathbb{P}_1)\backslash\{s_0\}$ to a vertex $m_1\in M\backslash R(\mathbb{P}_1)$ on a circuit L_1 in $G(\mathbb{P}_1)$. With P^1 and L_1, we change $\mathbb{P}^1$ and $\mathbb{P}_1$ as follows.

Let $P_i^1\in\mathbb{P}_1$ be a path maximally adjacent to P^1 with two vertices x_{i-1} and x_i with $1\le i\le k$, where $x_0=m_1'$ and $x_k=m_1$. Let P_1 be a path in $\mathbb{P}_1$ which ends at m_1. If P_1 is not identical to P_k^1, let P' and P'' be exchange paths of P_1 and P_k^1 by x_k, where $s(P')=s(P_k^1)$ and $s(P'')=s(P_1)$. Otherwise, let P' and P'' be exchange paths of P_1 and P_{k-1}^1 by x_{k-1}, where $s(P')=s(P_{k-1}^1)$ and $s(P'')=s(P_1)$. In the following, we consider the former case, because we have only to replace P_k^1 by P_{k-1}^1 for the case that P_1 is identical to P_k^1.

Let $\mathbb{P}^2=\mathbb{P}^1\backslash\{P_1,P_k^1\}\cup\{P',P''\}$. Then, obviously, $\mathbb{P}^2$ also satisfies (P1). For simplicity, only in this proof, let $s_1 = s(P_k^1)$. We classify P_k^1.

(Case 1) The case of $P_k^1 \in \mathbb{P}^1 \backslash \mathbb{P}_1$. Let $\mathbb{P}_2 = \mathbb{P}_1 \backslash \{P_1\} \cup \{P'\}$. Then, $\mathbb{P}_2$ satisfies (P2). It follows from $s(P_1) \notin R(\mathbb{P}_1)$ and (P2$''$) that $R(\mathbb{P}_1) \subseteq R(\mathbb{P}_2)$. Therefore, we consider the case $R(\mathbb{P}_1) = R(\mathbb{P}_2)$, which implies $s(P') = s_1 \notin R(\mathbb{P}_2)$. Furthermore, we consider two possible cases as follows.

(Case 1-1) $G(\mathbb{P}_1)$ contains a path from m_1 to s_1. In this case, $G(\mathbb{P}_2)$ contains a circuit including s_1 and m_1. Let L_2 be such a circuit. By replacing $\mathbb{P}^1$ and $\mathbb{P}_1$ by $\mathbb{P}^2$ and $\mathbb{P}_2$, respectively, we repeat the similar operation to P_{k-1}^1 and L_2 instead of P_k^1 and L_1.

(Case 1-2) $G(\mathbb{P}_1)$ contains no path from m_1 to s_1. In this case, note that the number of connected components of $G(\mathbb{P}_2)$ is less than that of $G(\mathbb{P}_1)$, which is used below. Moreover, it follows from (P2$'$) that $G(\mathbb{P}_2)$ contains a circuit reachable to s_1 and m_1. Let L_2 be such a circuit. Then, $N(\alpha, f)$ contains a path P^2 from a vertex $m_2' \in R(\mathbb{P}_2)$ to a vertex $m_2 \in M \backslash R(\mathbb{P}_2)$ on L_2. Let $P_2 \in \mathbb{P}_2$ be a path which ends at m_2. By replacing $\mathbb{P}^1$, $\mathbb{P}_1$, m_1' and m_1 by $\mathbb{P}^2$, $\mathbb{P}_2$, m_2' and m_2, respectively, we repeat the similar operation to P^2, P_2 and L_2 instead of P^1, P_1 and L_1.

(Case 2) The case of $P_k^1 \in \mathbb{P}_1$. Let $\mathbb{P}_2 = \mathbb{P}_1 \backslash \{P_1, P_k^1\} \cup \{P', P''\}$. Then, $\mathbb{P}_2$ satisfies (P2). If $s_1 \in R(\mathbb{P}_1)$, then by (P2$''$) we have $s_1 \in R(\mathbb{P}_2)$. This means that $G(\mathbb{P}_2)$ contains a path such as $s_1 \to m_1 \to \cdots \to s(P_1) \to t(P_k^1)$ including all vertices on L_1. Since $t(P_k^1) \in R(\mathbb{P}_2)$, we have $R(\mathbb{P}_1) \subseteq R(\mathbb{P}_2)$, which implies from $m_1 \in R(\mathbb{P}_2)$ that $R(\mathbb{P}_1) \subset R(\mathbb{P}_2)$. If $s_1 \notin R(\mathbb{P}_1)$, then $R(\mathbb{P}_1) \subseteq R(\mathbb{P}_2)$ because of $s(P_1) \notin R(\mathbb{P}_1)$ and (P2$''$). In addition, if $R(\mathbb{P}_1) = R(\mathbb{P}_2)$, then there holds $s_1 \in M \backslash R(\mathbb{P}_2)$. Therefore, $G(\mathbb{P}_2)$ contains a circuit L_2 including or reachable to s_1 and m_1. Now we can reduce this case to the case before classifying P_k^1.

Consequently, repeat the above operation as far as $R(\mathbb{P}_{i+1}) = R(\mathbb{P}_i)$ $(i \in \mathbb{Z}^+)$. We have $m_i' \in R(\mathbb{P}_i)$. Since the number of connected components of $G(\mathbb{P}_{i+1})$ never decreases to 0, we have Case 1-1 at some stage. As a result, we have a positive integer z such that $\mathbb{P}_z (\subseteq \mathbb{P}^z)$ contains a path P_z with a vertex $m_z' \in R(\mathbb{P}_z)$ and $m_z = t(P_z) \in M \backslash R(\mathbb{P}_z)$. For $s(P_z)$-m_z' and m_z'-m_z subpaths of $P_z \in \mathbb{P}^z$, denoted by P_z' and P_z'', respectively, let $\mathbb{P}^{z+1} = \mathbb{P}^z \backslash \{P_z\} \cup \{P_z', P_z''\}$ and $\mathbb{P}_{z+1} = \mathbb{P}_z \backslash \{P_z\} \cup \{P_z''\}$. Then, $\mathbb{P}^{z+1}$ satisfies (P1) and $\mathbb{P}_{z+1}$ satisfies (P2). It follows from $s(P_z) \in M \backslash R(\mathbb{P}_z)$ and (P2$''$) that $R(\mathbb{P}_z) \subseteq R(\mathbb{P}_{z+1})$, which implies from m_z' and P_z'' that $m_z \in R(\mathbb{P}_{z+1})$. Thus, we obtain $R(\mathbb{P}_z) \subset R(\mathbb{P}_{z+1})$. Hence, we have completed the proof. □

An arborescence is a directed tree where each vertex indegree is at most 1. It should be noted that any arborescence has exactly one vertex called a root with indegree 0.

The above lemma gives us the following proposition.

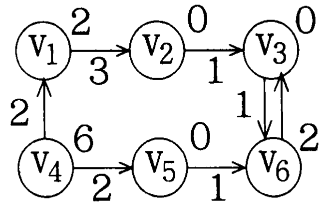

Fig. 3 A file transfer (ψ_3, f_3) on N_3.

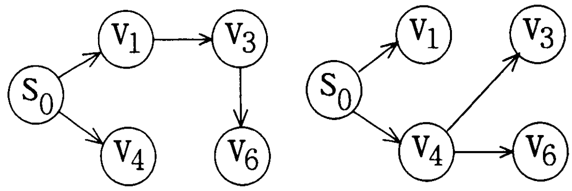

Fig. 4 Arborescences satisfying (P3).

Proposition 3: For a file transfer (ψ, f) on N such that $M \cup S \subseteq U$ and $M \backslash S \neq \phi$, let a function α on V satisfy Eq. (4). Then, we have a path set $\mathbb{P}$ satisfying (P1) as well as

(P3) $\mathbb{P}$ has a subset $\mathbb{P}'$ such that $G(\mathbb{P}')$ is an arborescence with a vertex set $\{s_0\} \cup S \cup M$ and root s_0.

Proof: For a path set satisfying (P1), let $\mathbb{P}_1$ be its subset satisfying (P2). Then, $R(\mathbb{P}_1) \subseteq s_0 \cup S \cup M$. If $R(\mathbb{P}_1) = \{s_0\} \cup S \cup M$, then the proposition holds as $\mathbb{P}' = \mathbb{P}_1$. Otherwise, by Lemma 7 we have another path set satisfying (P1) whose subset $\mathbb{P}_2$ satisfies $R(\mathbb{P}_1) \subset R(\mathbb{P}_2)$ as well as (P2). Since M is finite, we have the proposition. □

Note from (P1) that the outdegree of s_0 in $G(\mathbb{P}')$ is $|S|$ and the total arc number of $G(\mathbb{P}')$ is $|S \cup M|$.

Here is an example of this proposition. A file transfer (ψ_3, f_3) is shown in Fig. 3, on N_3 such that $S = \{v_1, v_4\}$, $s_V(v_1) = s_V(v_4) = 1$, $M = \{v_1, v_3, v_4, v_6\}$ and all copy demands are 2. The value near vertex v and arc e denotes $\psi_3(v)$ and $f_3(e)$, respectively, in Fig. 3, where an arc e with $f_3(e) = 0$ is omitted. From (ψ_3, f_3), more accurately, from its identical superimposition net, we can obtain some arborescences in (P3), two of which are shown in Fig. 4.

4. The Optimality of Forest-Type File Transfers

In the following, a directed forest is a directed graph whose underlying graph is a forest, where each vertex indegree is at most 1. In a directed forest, a vertex with indegree 0 is called a root. Note that an isolated vertex in a directed forest is also a root. If a directed forest contains an arc (x, y), then x is called the predecessor of y. We know that an arborescence is a directed forest with one root.

Here, we quote from [3] definitions relevant to a forest-type file transfer.

Definition 7[3]: If N satisfies $S \subseteq M$, then let $U' = U$. Otherwise, let U' be a set with each vertex in $S \backslash M$ twice and each vertex in $U \backslash (S \backslash M)$ once. Then, let a directed forest T satisfy

(CF) The vertex set is U' with root set S and each vertex in $U \backslash M$ is a leaf whose predecessor belongs to M.

In addition, for each arc (x, y) in T, let $\mathbb{P}_U$ be a path set with one minimum cost x-y path if $y \in M$ and otherwise $d(y)$-$s_V(y)$ minimum cost x-y paths. For $N(\alpha, \beta) = N(\mathbb{P}_U)$, a function α' on V is defined to be

$$\alpha'(u) = \begin{cases} \alpha(u) + d(u) - 1 & (u \in M), \\ 0 \quad (u \in V \backslash M). \end{cases}$$

Moreover, let $\mathbb{P}_S$ be a path set with $\alpha(u)$ minimum cost $h(u)$-u paths for each vertex u in $S \backslash M$ satisfying $\alpha(u) > 0$. Finally, let $N(\alpha_T, \beta_T)$ be the sum of $N(\alpha', \beta)$ and $N(\mathbb{P}_S)$. □

Note that if $S \backslash M \neq \phi$, then each vertex in $S \backslash M$ appears twice, that is, one as a root and another as a leaf in a directed forest satisfying (CF). In addition, a directed graph induced by an arc set $\{(s_0, u) |\ u \in S\} \cup B(T)$ for such directed forest T is an arborescence with root s_0.

We can derive the following propositions from Proposition 2, Lemmas 3 and 4 of [3].

Proposition 4[3]: Suppose that a directed forest T satisfy (CF) in N. Then, the net $N(\alpha_T, \beta_T)$ is a file transfer on N. In addition, let two disjoint subsets T_1 and T_2 of $B(T)$ be

$$T_1 = \{(x, y) \in B(T) |\ y \in U \backslash M\},$$
$$T_2 = B(T) \backslash T_1, \tag{5}$$

Then, $D_T = N(\alpha_T, \beta_T)$ satisfies

$$\begin{aligned} C(D_T) = & \sum_{u \in V \backslash M} \{c_V(h(u)) + c_{h(u),u}\{d(u) - s_V(u)\}\} \\ & + \sum_{u \in M} c_V(u) \cdot d(u) - \sum_{m \in S \cap M} c_V(m) \\ & + \sum_{(x,y) \in T_2} \{c_V(h(x)) + c_{h(x),x} + c_{x,y} - c_V(y)\}. \end{aligned} \tag{6}$$

□

Based on Proposition 4, the net obtained from a directed forest T satisfying (CF) is called a forest-type file transfer by T [3].

It follows from Eq. (5) and (CF) that each arc (x, y) of T_2 satisfies $y \in M \backslash S$. Therefore, a directed graph with arc set $\{(s_0, u) |\ u \in S\} \cup T_2$ is an arborescence with vertex set $\{s_0\} \cup S \cup M$ and root s_0. Thus, we have a path set $\mathbb{P}'$ satisfying (P3) such that $G(\mathbb{P}')$ is identical to such an arborescence.

We finally have the next conclusive proposition.

Proposition 5: For any file transfer D on N such that $M \cup S \subseteq U$, there exists a forest-type file transfer D_T satisfying $C(D) \geq C(D_T)$, where T is a directed forest satisfying (CF).

Proof: In order to prove the proposition, we suppose that the above $D = (\psi, f)$ satisfies (ψ_1). We consider the case $M \backslash S \neq \phi$ in the following, because otherwise we can prove in a similar way as $M \cap S = M$ and $T_2 = \phi$. For α defined as Eq. (4), by (P1) we have a path set $\mathbb{P}$ and a circuit set $\mathbb{L}$ such that $N(\mathbb{P} \cup \mathbb{L})$ is identical to $N(\alpha, f)$. Therefore, it follows from Eqs. (2) and (4) that

$$\begin{aligned} C(D) = & \sum_{P \in \mathbb{P}} \{c_V(s(P)) + c_B(P) - c_V(t(P))\} \\ & + \sum_{L \in \mathbb{L}} c_B(L) - \sum_{v \in V} c_V(v) \cdot s_V(v) \\ & + \sum_{v \in V} c_V(v) \cdot d(v). \end{aligned} \tag{7}$$

In addition, Proposition 3 says that there exists a path set $\mathbb{P}' (\subseteq \mathbb{P})$ satisfying (P3). As we can see through the above comment, we have such $\mathbb{P}'$ where $G(\mathbb{P}')$ is identical to an arborescence induced by a directed forest satisfying (CF). Let T' be the arc set of such an arborescence and let

$$T'' = \{(x, y) \in T' |\ y \in M \backslash S\}.$$

Note here that there exists an arc set T_2 of Eq. (5) which is identical to T''. Then, there holds $T'' = \{(s(P), t(P)) |\ P \in \mathbb{P}'\}$ from the definition of $G(\mathbb{P}')$. Hence, we have

$$\begin{aligned} & \sum_{P \in \mathbb{P}'} \{c_V(s(P)) + c_B(P) - c_V(t(P))\} \\ & \geq \sum_{(x,y) \in T''} \{c_V(x) + c_{x,y} - c_V(y)\} \\ & \geq \sum_{(x,y) \in T''} \{c_V(h(x)) + c_{h(x),x} + c_{x,y} - c_V(y)\}. \end{aligned} \tag{8}$$

We know that each path P in $\mathbb{P}$ satisfies $t(P) \in U$. Besides, if $t(P) \in M$, then we can see from Definition 2 that

$$\sum_{\substack{P \in \mathbb{P} \backslash \mathbb{P}' \\ t(P) \in M}} \{c_V(s(P)) + c_B(P) - c_V(t(P))\} \geq 0. \tag{9}$$

Note here that the equation holds for the case that $\mathbb{P} \backslash \mathbb{P}'$ has no path which ends at a vertex in M.

In addition, if a path P in $\mathbb{P} \backslash \mathbb{P}'$ satisfies $t(P) \in U \backslash M$, then $\psi(t(P)) = 0$ from (ψ_1). Thus, we can see from Eq. (4) that $\alpha(t(P)) \leq 0$, which implies that $\mathbb{P}$ has $|\alpha(t(P))| = d(t(P)) - s_V(t(P))$ paths. Conversely, if $t(P) \in U \backslash M$, then $P \notin \mathbb{P}'$. Hence, we have

$$\sum_{\substack{P \in \mathbb{P} \setminus \mathbb{P}' \\ t(P) \in U \setminus M}} \{c_V(s(P)) + c_B(P) - c_V(t(P))\}$$
$$\geq \sum_{v \in V \setminus M} \{c_V(h(v)) + c_{h(v),v} - c_V(v)d(v) - s_V(v)\}. \tag{10}$$

Note here that $\alpha(v) = 0$ for $v \in V \setminus U$. Hence, after we rearrange Eq. (6) by substituting Eqs. (8)–(10) into Eq. (7), we obtain $C(D) \geq C(D_T)$. □

The proposition says that we have only to consider forest-type file transfers by T satisfying (CF) in order to obtain an optimal file transfer. In [3], we mention how to obtain a forest-type file transfer with minimum cost, i.e., an optimal file transfer.

5. Conclusion

This paper has shown that, on a file transmission net N where to each source vertex one copy of J is given, it suffices to consider forest-type file transfers in order to obtain an optimal file transfer.

The future task is to deal with more general class of N, e.g., to source vertex more than one copy of J is given or with source vertex whose copy demand is 0 and so forth. In such a situation, we might modify the definition of forest-type file transfer so as to obtain an optimal file transfer. Another interesting problem is to classify N based on graph structures such as tree, bipartite graph, planar graph and so forth.

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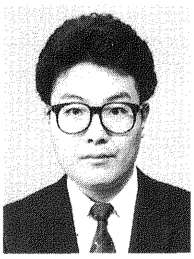

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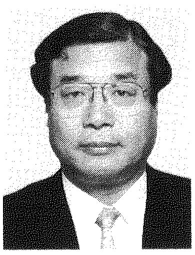

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