PAPER

A Scheduling Problem in Multihop Networks

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SUMMARY In a multihop network, radio packets are often relayed through inter-mediate stations (repeaters) in order to transfer a radio packet from a source to its destination. We consider a scheduling problem in a multihop network using a graphtheoretical model. Let $D = (V, A)$ be the digraph with a vertex set V and an arc set A. Let f be a labeling of positive integers on the arcs of A. The value of $f(u, v)$ means a frequency band assigned on the link from u to v. We call f antitransitive if $f(u, v) \neq f(v, w)$ for any adjacent arcs (u, v) and (v, w) of D. The minimum antitransitive-labeling problem is the problem of finding a minimum antitransitive-labeling such that the number of integers assigned in an antitransitive labeling is minimum. In this paper, we prove that this problem is NP-hard, and we propose a simple distributed approximation algorithm for it.
key words: *multihop network, mobile communication, graph theory, NP-complete problem, cut covering*

1. Introduction

A multihop network has been considerable interest. In such a network, radio packets are employed for communication, and are often relayed through intermediate stations (repeaters) in order to transfer a message from a source to its destination. Figure 1 illustrates a multihop network. Each intermediate station can reuse channels/slots. Scheduling problems in multihop networks have been discussed on a system using frequency/time division multiple access (FDMA/TDMA). Ramanathan and Lloyd used edge-and-vertex coloring problems on the graph theory as a model for problems of assigning channels/slots in FDMA/TDMA [8]. Chlamtac and Pinter considered the vertex coloring problem, and presented the distributed algorithm for it [2]. Hajek and Sasaki applied the fraction edge-coloring problem, and presented a polynomial time algorithm for it [4]. In this paper we employs a graph model in order to consider a scheduling problem, which can be applied to a multihop network using code division multiple access (CDMA).

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Let's provide a graph model of a multihop network. Let $D = (V, A)$ be the simple digraph with a vertex set V and an arc set A. A vertex of V corresponds to a station in a radio network, and an arc (u, v) of A corresponds to the unidirectional communication link from u to v. Let f be a labeling on positive integers on the arcs of A. The value of $f(u, v)$ means a frequency band assigned on the link from u to v. In a multihop network, each station often intermediates radio packets. We assume that each station can receive and send packets simultaneously, and that can not use a frequency band common to reception and transmission. But the CDMA nature allows that an identical frequency band is associated with plural received packets (respectively, sent packets). These assumptions indicate the following condition: $f(u, v) \neq f(v, w)$ for any adjacent arcs (u, v) and (v, w) of D.

If a labeling f satisfies this condition, then we call f antitransitive. Figure 2 shows an example of an antitransitive labeling. We define the size of f as follows:

$$|\{f(a) \mid a \in A\}|.$$

The antitransitive-labeling is minimum if the size of it is equal to $\min_f |\{f(a) \mid a \in A\}|$. The minimum antitransitive-labeling problem (called Min-ATLP) is

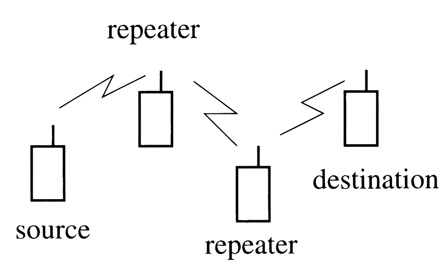

Fig. 1 Multihop network.

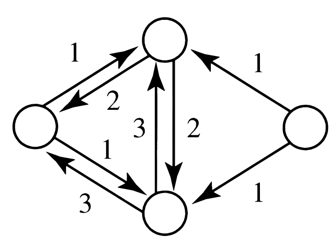

Fig. 2 Antitransitive labeling.

the problem of finding a minimum antitransitive-labeling. In Sect. 2 we consider the properties of a minimum antitransitive labeling, and we show that Min-ATLP is equivalent to the cut cover problem. In Sect. 3 we prove that Min-ATLP is NP-hard, and in Sect. 4 we propose a simple distributed approximation algorithm for it (Readers that are not interested in proofs, and complexity may just see Sect. 4.).

2. Properties

In this paper a cut denotes the set of arcs incident from V' to $V-V'$ for some subset V' of V. A cut cover in a digraph D is a family of directed cuts such that each arc of A belongs to some cut of this family. A minimum cut cover in D is one of the minimum size, and $c(D)$ denotes the size of a minimum cut cover. Motwani and Naor considered the undirected version of this problem [7]. They showed that $c(G) = \lceil \lg \chi(G) \rceil$ for any undirected graph G where $\chi(G)$ is the chromatic number of G, proved the problem of finding a minimum cut cover of graphs is NP-complete, and consider hardness of its approximation.

For any nonnegative integer k, a k-cut cover is a cut cover of at most size k, and an antitransitive k-labeling is an antitransitive labeling of at most size k. Hereafter we suppose that $1 \le f(a) \le k$ for any antitransitive k-labeling f without loss of generality. We prove the following lemma.

Lemma 1: A digraph D has an antitransitive k-labeling if and only if D has a k-cut cover.

proof: To begin with, we show the necessary condition. Let f be an antitransitive k-labeling in D. For any $1 \le i \le k$, let U_i be the set of vertices incident to the arcs of label i. Then there is not an arc of label i incident from-and-to vertices of U_i. Hence the cut from U_i to $V-U_i$ contains all the arcs of label i. Therefore the family $\{C_1, \ldots, C_k\}$ is a k-cut cover in D where C_i denotes the cut from U_i to $V-U_i$.

Next we show the sufficient condition. Let $\{C_1, \ldots, C_k\}$ be a k-cut cover of D, and label each arc a as an arbitrary integer i such that $a \in C_i$. Then such a labeling is antitransitive, and the number of its labels is equal or less than k. □

This lemma tells us that $c(D)$ is equal to the size of a minimum antitransitive labeling. If we know an antitransitive k-labeling in digraphs, then we easily obtain the k-cut covering. And the converse also holds. For an antitransitive labeling in D, if all of the arcs opposite to the arcs of a label have an equal label, then we say such an antitransitive labeling to be symmetric. Finding a symmetric antitransitive-labeling in D comes to finding an undirected cut cover in the underlying graph of D. Let $c'(D)$ be the size of a minimum symmetric antitransitive-labeling in D. The report [7] tells us that $c(G) = \lceil \lg \chi(G) \rceil$ for any undirected graph G, where $c(G)$ is the number of cuts of a minimum undirected-cut cover in G. Hence we obtain $c'(D) = 2\lceil \lg \chi(D) \rceil$. We can not exactly characterize $c(D)$ by chromatic number like $c'(D)$. Let's see the upper and lower bounds of $c(D)$. We can obtain the following lemma in the way similar to the undirected version [7].

Lemma 2: For any digraph D,

$$\lg \chi(D) \le c(D).$$

Now let's prove the following lemma about an upper bound of $c(D)$.

Lemma 3: For any digraph D,

$$c(D) \le \lceil \lg \chi(D) \rceil + \lceil \lg \lceil \lg \chi(D) + 1 \rceil \rceil.$$

proof: Let $g: V \to \{0, \ldots, \chi(D)-1\}$ be an optimum coloring in D. For each vertex x of D, let $s(x)$ denote the $\lceil \lg \chi(D) \rceil$-bit binary notation of $g(x)$, and let $s_i(x)$ denote the ith bit of $s(x)$. For any arc (u,v) of A, if there exists some integer i such that $s_i(u) = 1$ and $s_i(v) = 0$, then we label the arc (u,v) as i. Let A' be the set of the labeled arcs. Then such a labeling is antitransitive in the subdigraph (V, A') of D. Let $A'' = A - A'$. We again examine the binary notation $s'(x)$, the number of negative bits in $s(x)$ for any vertex x of D'. The binary sequence $s'(x)$ needs only $\lceil \lg \lceil \lg \chi(D) + 1 \rceil \rceil$ bits this time. We label each arc (u,v) of A'' as an arbitrary integer $i + \lceil \lg \chi(D) \rceil$ such that $s'_i(u) = 1$ and $s'_i(v) = 0$. We must verify that all arcs of A have been labeled to prove this theorem completely. Let (u,v) be an arc of A. If $(u,v) \in A'$, then this arc is labeled clearly. So we consider the case where $(u,v) \in A''$. By the definition of s_i, we derive

$$\{i : s_i(v) = 0\} \subseteq \{i : s_i(u) = 0\}.$$

Since f is a coloring, the equality is not valid. Hence we obtain

$$|\{i : s_i(v) = 0\}| < |\{i : s_i(u) = 0\}|.$$

Thus there exists an integer i such that $s'_i(u) = 1$ and $s'_i(v) = 0$. Therefore the arc (u,v) has been labeled. If there exists an arc (v,w) of A'' adjacent from (u,v), then $s'_i(v) = 0$, and so the label of (v,w) is not equal to $i + \lceil \lg \chi(D) \rceil$. This result implies that the obtained labeling is antitransitive in the subdigraph (V, A'') of D. Hence the digraph D has an antitransitive labeling of size $\lceil \lg \chi(D) \rceil + \lceil \lg \lceil \lg \chi(D) + 1 \rceil \rceil$. □

Using the above two lemmas, we obtain the following theorem

Theorem 1: For any digraph D,

$$\lg \chi(D) \le c(D) \le \lceil \lg \chi(D) \rceil + \lceil \lg \lceil \lg \chi(D) + 1 \rceil \rceil.$$

Let K_n be the digraph with n vertices such that there exist the arc (u,v) and (v,u) for any different vertices u and v in K_n. (The chromatic number $\chi(K_n)$ is equal

Table 1 $c(K_n)$, and $\lceil \lg n \rceil + \lceil \lg \lceil \lg n + 1 \rceil \rceil$.

n	$c(K_n)$	$\lceil \lg n \rceil + \lceil \lg \lceil \lg n + 1 \rceil \rceil$
1	0	0
2	2	2
3	3	4
4	4	4
5	4	5
6	4	5
7	5	5

to n). None know the exact value of $c(K_n)$ for a large n. Table 1 shows that the values of $c(K_n)$, and $\lceil \lg n \rceil + \lceil \lg \lceil \lg n + 1 \rceil \rceil$.

A tournament T is an asymmetric complete digraph, that is, a digraph such that either (u, v) or (v, u) is an arc of T for any different vertices u and v of T. A tournament T is transitive if whenever (u, v) and (v, w) are arcs of T, then (u, w) also is an arc of T. The following lemma holds.

Lemma 4: If a tournament T with n vertices is transitive, then

$$c(T) = \lceil \lg n \rceil.$$

proof: Let T be a transitive tournament with n vertices. From Lemma 2 we obtain $\lg \chi(T) = \lg n \leq c(T)$. Now we show $c(T) \leq \lceil \lg n \rceil$. The score of a vertex of T is the outdegree of this vertex. Reference [1] tells us that for any score $0 \leq s \leq n-1$, there exists the unique vertex of T with score s. Considering the $\lceil \lg n \rceil$-bit binary notations of scores in the same way of Lemma 3, we can obtain an antitransitive $\lceil \lg n \rceil$-labeling in T. $\Box$

Using this lemma, we obtain the following lemma.

Lemma 5: Let T be a transitive tournament with n vertices where $n = 2^m$ for some nonnegative integer m, and let u be the vertex of the maximum outdegree $n-1$. If an m-labeling in T is antitransitive, then there exists an arc of the label i incident from u for any label i.

proof: Suppose that this lemma is false. Then there exists a label i of some antitransitive labeling such that i is not equal to the label of any arc incident from u. Let x be a new vertex, let $B = \{(x, v) | v \in V(T)\}$, and T' be the transitive tournament obtained by adding the arcs of B to T. Then we can label the arc (x, u) as i, and each arc (x, v) of $B - \{(x, u)\}$ as a label equal to the label of (u, v). The obtained m-labeling of T' is antitransitive. However we obtain $c(T') = m + 1$ from Lemma 2. Hence we have a contradiction. Thus we have proved this lemma. $\Box$

3. NP-Completeness Results

In this section, we prove NP-completeness results for subproblems. For a fixed integer $k \geq 0$, we define the decision problem whether there exists an antitransitive k-labeling in a digraph as follows.

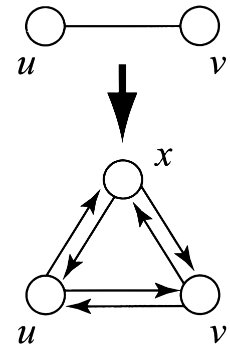

Fig. 3 Replacement of the edge (u, v).

k-ATLP
Instance : A digraph $D = (V, A)$.
Question: $c(D) \leq k$? $\Box$

We show that k-ATLP is NP-complete by reducing the following GRAPH k-COLORABILITY to k-ATLP for any $k \geq 3$.

GRAPH k-COLORABILITY
Instance : A graph $G = (V, E)$.
Question: Is there a k-coloring g in D? That is, is there mapping $g : V \to \{1, \ldots, k\}$ such that $g(u) \neq g(v)$ for any edge $\{u, v\}$ of E? $\Box$

It is well-known that GRAPH k-COLORABILITY is NP-complete for any fixed integer $k \geq 3$ (see Ref. [3]).

Theorem 2: The 3-ATLP problem is NP-complete for planar symmetric digraphs. (A digraph D is symmetric if $(u, v) \in A$ for any $(v, u) \in A$.)

proof: It is easy to see that 3-ATLP belongs to NP. We transform GRAPH 3-COLORABILITY to this problem. Let $G = (V, E)$ be the graph in an instance of GRAPH 3-COLORABILITY. First, for each edge $\{u, v\}$ of E, we add new vertex x to G, and two edges $\{u, x\}$ and $\{v, x\}$. Let $G' = (U, E')$ be the graph obtained by above the addition. Next we replace each edge of the graph G' with two opposite arcs. Figure 3 shows such replacement. Let $D = (U, A)$ be the digraph obtained by this replacement. Clearly D can be constructed from G in polynomial time.

We show that G is 3-colorable iff $c(D) \leq 3$. Suppose that G is 3-colorable. Then there exists a vertex coloring $g : V \to \{1, 2, 3\}$. We associate a color $g'(u)$ with each vertex u in D as follows: if a vertex u of D belongs to V, then let $g'(u) = g(u)$; and otherwise let $g'(u)$ be the color of $\{1, 2, 3\}$ not used on the two vertices adjacent to u. Then g' is a 3-coloring in D. For each vertex v of D, we assign $g'(v)$ to labels of the arcs incident from v. Since g' is a 3-coloring in D, the obtained 3-labeling is antitransitive. Hence $c(D) \leq 3$.

Conversely assume that $c(D) \leq 3$. Then there exists an antitransitive 3-labeling in D. In this paper we say the digraph K_3, illustrated in Fig. 3, to be a triangle, and a symmetric digraph whose arcs are always

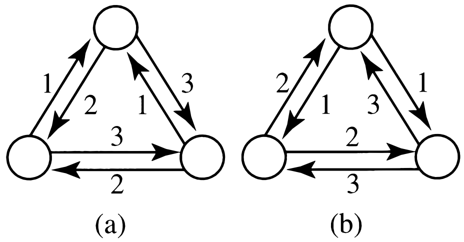

Fig. 4 (a) Incoming labeling, (b) outgoing labeling.

involved in a triangle to be triangulated. The transformed digraph D is triangulated. The number of antitransitive 3-labelings in a triangle are only two, but there is not an antitransitive 2-labeling in a triangle. Figure 4 illustrates the two antitransitive labelings of a triangle. In the labeling of Fig. 4(a) (resp., Fig. 4(b)), the arcs incident to (from resp.) a vertex have the same label. So we call such a labeling of a triangle an incoming (outgoing resp.) labeling. We can suppose that D is connected without loss of generality. We prove the following lemma.

Lemma 6: For a triangulated connected-digraph D with an antitransitive 3-labeling, if the restriction of this labeling on one triangle of D is incoming (outgoing resp.), then that on the others are incoming (outgoing resp.).

proof: If the number of triangles is equal to unity, that is, the digraph D consists of a triangle, then the lemma is trivial. We prove the lemma in the case where the number of triangles is equal or more than two. Assume that the lemma are false. Then there exist a triangle T_1 with a incoming labeling, and a triangle T_2 with a outgoing labeling such that T_1 and T_2 share in some vertex. The labels of the four arcs incident from this vertex in T_1, or incident to the vertex in T_2 must be disjoint. This result contradicts that D has antitransitive 3-labeling. Hence the lemma holds in the case where the number is equal or more than two. □

We return the proof of Theorem 2. From Lemma 6, the antitransitive labeling in D is either incoming or outgoing. If all the triangles in D have an incoming (outgoing resp.) labeling, then we associate with each vertex v of D the integer $g(v) \in \{1, 2, 3\}$ equal to the label of the arcs incident to (from resp.) v. Then $g(x) \neq g(y)$ for any adjacent vertices x and y in D. Thus the restriction of g on V is a 3-coloring in G. Hence G is 3-colorable iff D has a 3-cut cover, and so 3-ATLP is NP-complete for symmetric digraphs.

GRAPH 3-COLORABILITY is NP-complete even for a planar graph [3]. If G is planar, then D is planar. Hence 3-ATLP is NP-complete even for symmetric planar digraphs. We have proved Theorem 2. □

We can find a 4-coloring $g : V \to \{1, 2, 3, 4\}$ of planar digraphs in polynomial time [5]. If we know a 4-coloring g of a planar digraph, then we can provide an antitransitive 4-labeling f such that $f(u, v) = g(u)$ for any u of A. Hence 4-ATLP for planar digraphs is solvable in polynomial time.

Now we prove the following theorem.

Theorem 3: For any fixed integer $k \geq 4$, the k-ATLP problem is NP-complete.

proof: Clearly k-ATLP belongs to NP. We transform from GRAPH k-COLORABILITY to k-ATLP. Let $G = (V, E)$ be the graph in an instance of GRAPH k-COLORABILITY. Let $n = 2^{k-1}$, and let T be a transitive tournament with n vertices. First we replace each edge $\{x, y\}$ with the arcs (x, y) and (y, x). Next for each vertex v of the digraph obtained by this replacement, we make a copy of T, and identify v with the vertex of outdegree $n - 1$ in this copy. Since k is fixed, we can accomplish this transformation in polynomial time.

Let D denote the transformed digraph. We show that if G is k-colorable, then $c(D) \leq k$. Suppose that G is k-colorable. Then there exists a coloring $g : V \to \{1, \dots, k\}$ in G. For each vertex v of V, we associate $g(v)$ with labels of all the arcs incident to v. From Lemma 5, for any vertex v of V, we can associate the arcs of the copy of T incident from v with antitransitive labels of $\{1, \dots, k\} - \{g(v)\}$. Hence D has an antitransitive k-labeling, and so $c(D) \leq k$.

Conversely assume that $c(D) \leq k$. Then there exists an antitransitive k-labeling in D. Using Lemma 5, all labels are equal on the arcs incident to v for each vertex v of V. Let $g(v)$ be the integer equal to such a label. Then g is a k-coloring in G, and so G is k-colorable. We have proved the theorem. □

4. Approximation Algorithm

In this section we consider an approximation algorithm for Min-ATLP. In the proof of Lemma 3, we obtain an antitransitive labeling using an optimal coloring. In the same way, if we know an $h(D)$-coloring of D, then we can obtain an antitransitive labeling of size $\lceil \lg h(D) \rceil + \lceil \lg \lceil \lg h(D)+1 \rceil \rceil$. An approximation algorithm is shown as follows.

Algorithm 1

Step 1) Find an m-coloring $g : V \to \{0, \dots m-1\}$ of a digraph D. (Let $m' = \lceil \lg m \rceil$.)

Step 2) For each arc (u, v) of D,

Step 2.1) If there exists some positive integer k such that the kth bit in the m'-bit binary notation of $g(u)$ is positive, and such that $g(v)$ negative, then assign k to (u, v).

Step 3) For any vertex x, let $g'(x)$ be the number of negative bits in m'-bit binary notation of $g(x)$.

Step 4) For each arc (u, v) of D that Step 2.1 did not assign,

Step 4.1) If there exists some positive integer k such

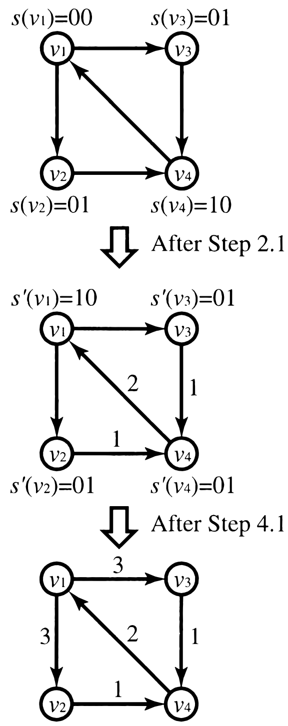

Fig. 5 An example of behavior of algorithm 1.

that the kth bit in the $\lceil \lg m' + 1 \rceil$-bit binary notation of $g'(u)$ is positive, and such that $g'(v)$ negative, then assign $k + m'$ to (u, v).

Figure 5 illustrates an example of behavior of this algorithm. In a multihop network, scheduling algorithms need to be distributed. We can easily obtain the distributed version of the algorithm. The distributed coloring algorithm [6] can find $d(D)$-coloring in polynomial time, where $d(D)$ is the maximum degree of the underlying graph of D. Hence there exists a distributed algorithm that finds $(\lceil \lg d(D) \rceil + \lceil \lg \lceil \lg d(D) + 1 \rceil \rceil)$-antitransitive labeling in a polynomial time.

5. Conclusion

In this paper we discuss a scheduling problem in a multihop network. We consider Min-ATLP as this problem, prove that Min-ATLP is NP-hard, and present that there exists a distributed algorithm that finds $(\lceil \lg d(D) \rceil + \lceil \lg \lceil \lg d(D) + 1 \rceil \rceil)$-antitransitive labeling in polynomial time.

We do not exactly know the upper bound of $c(D)$, and the value of $c(K_n)$. Strictly evaluating them is an open problem. As future research, we will find a better heuristics than digraph coloring.

References

[1] G. Chartrand and L. Lesniak, Graphs & digraphs, Chapman & Hall, 1996.
[2] I. Chlamatac and S. Pinter, "Distributed node organization algorithm for channel access in a multihop dynamic radio network," IEEE Trans. Comput., vol.C-36, no.6, pp.728–737, June 1987.
[3] M.R. Garey and D.S. Johnson, Computers and intractability: A guide to the theory of NP-completeness, Freeman, San Francisco, 1979.
[4] B. Hajek and G. Sasaki, "Link scheduling in polynomial time," IEEE Trans. Inf. Theory, vol.34, no.5, pp.910–917, Sept. 1987.
[5] T.R. Jensen and B. Toft, Graph coloring problems, A Wiley-Interscience Publication, 1995.
[6] N.A. Lynch, Distributed algorithms, Morgan Kaufmann Publishers, 1997.
[7] R. Motwani and J.S. Naor, "On exact and approximate cut covers of graphs," Technical Report STAN-CS-TN-94-11, Dept. of Computer Science, Stanford University, 1994.
[8] S. Ramanathan and E.L. Lloyd, "Scheduling algorithms for multihop radio networks," IEEE/ACM Trans. Networking, vol.1, no.2, pp.166–177, April 1993.

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