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FICTC: fault-tolerance-and-interference-aware topology control for wireless multi-hop networks

Xuecai Bao[1,2*] and Chengzhi Deng[1,2]

Abstract

K-connectivity-based topology control can improve fault-tolerant performance of multi-hop wireless networks. Existing algorithms mainly focused on preserving the same *k*-connectivity between any two nodes. However, in practical network deployments, the algorithms enforcing *k*-connectivity degrade network performance, when the topology requires heterogeneous nodal fault-tolerant requirements. In this paper, we aim to develop interference-aware topology control based on the different k_{ij} connectivities between any two nodes and propose a fault-tolerance-and-interference-aware topology control (FICTC) algorithm. It can be proved that FICTC can meet different fault-tolerant requirements between any two nodes, and is the optimum solution for min-max network interference. Simulation results show that FICTC not only leads to weaker interference, but also achieves higher throughput and lower end-to-end (E2E) delay than existing fault-tolerant topology control schemes.

Keywords: Interference-aware topology control, Fault-tolerance constraints, Wireless multi-hop network

1 Introduction

In wireless multi-hop networks (WMNs), source and destination nodes leverage two or more hops for information delivery. WMNs have several well-known examples, such as wireless mesh network, ad hoc networks, and wireless sensor networks (WSNs). In these scenarios, energy-efficiency and network capacity are the most two concerned issues. Topology control techniques, as highlighted in [1], are promising to address both issues. Generally, topology control can be divided into two classes, namely, connectivity-preserving topology control and *k*-connected fault-tolerant topology control, respectively. The connectivity-preserving topology control aims to maintain network connectivity via smaller nodal transmit powers. There also exist algorithms concerning the trade-off between energy conservation and network connectivity [2–11].

However, under such a paradigm, nodes or link failures lead to performance degradation, even causing service interruption. In order to ensure fault-tolerance, *k*-connectivity topology control has been studied [12–17]. These mentioned algorithms focused on finding a sub-graph with *k*-node-disjoint paths between any two nodes, wherein most of them aim to find *k*-connected sub-graphs consuming minimum total power or minimized maximum power. Besides, some algorithms investigated the topology control based on minimizing the maximum interference rather than addressing the fault-tolerant requirement [18–21].

However, in practical network deployments, it is not required that each node has to be *k*-connected to other nodes, i.e., only a few nodes requiring *k*-connected, while remaining nodes are less *k*-connected, i.e., the practical networks often require different k_{ij} connectivities between any two nodes.

Therefore, the purpose of this paper is to solve the topology control problem that minimizes the maximum node interference for WMNs with different k_{ij} connectivity requirements between any two nodes. In this paper, we firstly analyze the differences between specific k_{ij} connectivity and *k*-connected requirements and present the problem formulation. Then, we propose a fault-tolerance-and-interference-aware topology control

* Correspondence: lx97821@126.com
[1]Jiangxi Province Key Laboratory of Water Information Cooperative Sensing and Intelligent Processing, Nanchang Institute of Technology, 330099 Nanchang, Jiangxi, China
[2]School of Information Engineering, Nanchang Institute of Technology, 330099 Nanchang, Jiangxi, China

(FICTC) algorithm, which not only satisfies different fault-tolerance requirements between any two nodes but also minimizes the maximum nodal interference. The main contributions of this paper are as follows.

(1) We investigate the practical requirement of topology control with different k_{ij} connectivity requirements between any two nodes and the difference of network performance influence between specific k_{ij} connectivity and k-connected requirements.
(2) We integrate the minimize the maximum node interference into the topology control with different k_{ij} connectivity requirements between any two nodes and present the detail steps of our proposed algorithms.
(3) We achieve minimizing the maximum node interference for attaining specific k_{ij} connectivity between any two nodes and the finally extensive experiments by simulations to evaluate the performance of the proposed algorithms.

The rest of the paper is organized as follows. Section 2 summarizes related works for k-connected topology control. Section 3 defines the network and interference model, and presents the problem formulation of topology control with fault-tolerance constraints. We then present FICTC and theoretical analysis of the proposed FICTC in Section 4. The distributed implementation of the proposed FICTC is presented in Section 5. Performance evaluation of FICTC and comparisons with other state-of-the-art algorithms are given in Section 6. Section 7 concludes our work and contributions.

2 Related work

Topology control can reduce interference and energy consumption. Moreover, it can improve network performance, such as network capacity, fault-tolerance, and scalability [2–24]. Typically, topology control algorithms can be categorized by preserving 1-connectivity and k-connectivity, respectively. For preserving 1-connectivity, current works mainly focused on prolonging network lifetime and increasing network capacity, without considering topology fault-tolerance [2–11, 25]. To achieve fault-tolerance, algorithms that construct k-connected topologies have been proposed [12–24]. In [12], the relationship between k-connectivity and node degree was described. Then, the authors presented an algorithm that can preserve k-connectivity. However, the minimum node degree was not given. Fukunaga et al. [22] derived an analytical expression of minimum node degree for constructing k-connected topology with a high probability. Based on Yao structure ($YAO_{p,k+1}$), Li et al. proposed an algorithm to sustain k-connectivity. The key issue is to assume there are p equal cones around one node and choose $k+1$ closest nodes in each cone. Li et al. [23] proposed the communications-based train control (CBTC) algorithm. In CBTC, each node needs to link at least one node in every cone of degree a centered at this node. Meanwhile, they proved that it can preserve k-connectivity when $a < 2\pi/3k$. Li et al. [13] developed centralized $FGSS_k$ and localized $FLSS_k$ algorithms, which both guarantee k-connectivity when a unit disk graph (UDG) is k-connected. The $FGSS_k$ and $FLSS_k$ are min-max optimal. Miyao et al. [14] gave out a k-connectivity-preserving algorithm with lower time complexity, called local tree-based reliable topology (LTRT). However, it only guarantees k-edge connectivity while takes no account of k-node connectivity. Wang et al. [15] proposed a k-connected energy-aware algorithm and proved the total power consumption is minimum. Bagci et al. [16] presented a distributed fault-tolerant algorithm. Zhao et al. [17, 18, 24] studied the schemes based on cooperative communication to achieve topology control, and Guo et al. [19] present a more efficient fault-tolerant topology control with k-connectivity. By exploiting the advantage of cooperative communications, it can achieve path energy-efficiency and lower power consumption. Ao et al. [20] consider topology control with opportunistic interference cancelation. Luo et al. [21] provide the optimization problem of joint topology control and authentication design in mobile ad hoc networks with cooperative communications. Burkhart et al. [26] revealed that the minimum total power does not lead to minimum interference. Recently, mobile crowd sensing-based method [27–29] is proposed to process social sensing data.

Although the above algorithms can perform k-connectivity with high energy efficiency, few researches consider heterogeneous nodal fault-tolerant requirements, i.e., node v_i should be k_{ij}-connected to node v_j and there are different k_{ij} connectivities between any two nodes.

3 Related model and problem formulation

3.1 Network model

We consider a WMN as an undirected physical topology graph $G(V, E)$, where $V = \{v_1, v_2, \ldots, v_i, v_{i+1}, \ldots, v_n\}$ is the set of n vertices, i.e., routers, and $E = \{e_{ij}\}$ is the set of all edges. The involved links are symmetric for simplicity, i.e., for v_i and v_j in an obstacle-free environment; if there exists a link between them, then the channel is reciprocal. Each node is equipped with an omnidirectional antenna and the same maximum transmit power $p_{\max}$, associated with the maximum transmit range $r_{\max}(p_{\max})$. Let $d(v_i,v_j)$ be the distance between v_i and v_j. If $d(v_i,v_j) \le r(p_i)$, where $r(p_i)$ is the transmit range of v_i with power p_i $(0 \le p_i \le p_{\max})$, then a link e_{ij} exists from v_i to v_j. Meanwhile, we use the unit disk graph (UDG) to model our topology, i.e., all nodes have the same transmit range. It is noted that UDG is a topology derived via the maximum transmit radius, which corresponds to a transmit power of 0.28183815 W under free space propagation model.

3.2 Interference model

Interference reduction is one of the major goals in topology control, and most algorithms achieve so by minimizing the node degree, as small node degree leads low interference. However, [26] found the minimum node degree does not imply the minimum interference. Existing interference models are divided into physical interference models and protocol interference ones [25, 30, 31]. Physical interference model is defined by formula (1), where β is the minimum signal to noise ratio (SNR) for successful receptions, N is the ambient noise power level, and a denotes the signal power decays with respect to $d(v_i,v_j)$, p_k and p_i denote the power level chosen by node v_k and v_i, respectively.

$$\frac{p_i d(v_i, v_j)^{-a}}{N + \sum_{k \in V} p_k d(v_k, v_j)^{-a}} \geq \beta \quad (1)$$

Although physical interference model is convenient for analysis, it is affected by β, N, a, and p_k [30]. We thus need to have these parameters to calculate the interference; in turn, the parameters need to be adjusted by minimizing the interference. In this regard, it is extremely difficult to calculate the interference. In this work, we use protocol model to describe interference [30, 32].

Before introducing the interference model, we present the concept of transmission range and interference range. Transmission range and interference range are two important radio ranges in wireless networks. Transmission range represents the range within which a packet is successfully received if there is no interference from other radios. The transmission range is mainly determined by transmission power and radio propagation properties (i.e., attenuation). Interference range (Ri) is the range within which stations in receive mode will be “interfered with” by an unrelated transmitter and thus suffer a loss [31]. For a node v_i with a transmit range $r(v_i, v_j)$ and interference range $r_I(v_i, v_j)$, v_i sends data to v_j, then the number of nodes within $r_I(v_i, v_j)$ is called *unidirectional link interference set*, denoted as $ULIS(v_i, v_j)$:

$$ULIS(v_i, v_j) = \{v_w \in V | d(v_i, v_w) \leq r_I(v_i, v_j)\} \quad (2)$$

Since link (u, v) is bidirectional, $ULIS(v, u)$ can be defined as

$$ULIS(v_j, v_i) = \{v_w \in V | d(v_j, v_w) \leq r_I(v_j, v_i)\} \quad (3)$$

Therefore, the interference set of (u, v) is

$$LIS(v_i, v_j) = ULIS(v_i, v_j) + ULIS(v_j, v_i) \quad (4)$$

where $LIS(v_i, v_j)$ is the interference level. In order to build an interference efficient spanning sub-graph, $LIS(v_i, v_j)$ is used as the weight of edge (v_i, v_j). Moreover, we define the $LIS(G)$ as interference matrix, i.e., the $LIS(G) = \{ LIS(v_1, v_1), LIS(v_1, v_2), LIS(v_1, v_3),\ldots, LIS(v_1, v_n); LIS(v_2, v_1), LIS(v_2, v_2), LIS(v_2, v_3),\ldots, LIS(v_2, v_n);\ldots; LIS(v_n, v_1), LIS(v_n, v_2), LIS(v_n, v_3),\ldots, LIS(v_n, v_n)\}$.

Furthermore, to ensure different weights between any two edges, we use the *id* of the nodes [13]. The meaning of *id* is the node number, such as, in Fig. 1, the *id* of node v_i is i. Specifically, given four different edges (v_1, v_2), (v_3, v_4), (v_1, v_3) and (v_2, v_3), the rules for comparing the weight size of edges (v_1, v_2), (v_3, v_4) and edges (v_1, v_3), (v_2, v_3) are defined as

$$\begin{aligned}
&w(v_3, v_4) > w(v_1, v_2) \\
&\Leftrightarrow LIS(v_3, v_4) > LIS(v_1, v_2) \\
&\quad or \quad LIS(v_3, v_4) = LIS(v_1, v_2) \\
&\{\max\{id(v_3), id(v_4)\} = 4\} > \{\max\{id(v_2), id(v_1)\} = 2\} \\
&w(v_2, v_3) > w(v_1, v_3) \\
&\Leftrightarrow LIS(v_2, v_3) > LIS(v_1, v_3) \\
&\quad or \quad LIS(v_2, v_3) = LIS(v_1, v_3) \\
&\{\max\{id(v_2), id(v_3)\} = 3\} = \{\max\{id(v_1), id(v_3)\} = 3\} \\
&\{\min\{id(v_2), id(v_3)\} = 2\} > \{\min\{id(v_1), id(v_3)\} = 1\}
\end{aligned}$$

If the *ids* of end-nodes for each edge are different, then each edge has different weight. Therefore, the weight function will ensure the uniqueness in process of adding edges.

3.3 Problem formulation

Preserving network connectivity or k-connectivity may not meet network performance. For example, in Fig. 2a, b, both networks are 2-connected graphs, while with different fault-tolerant requirements. Furthermore, transmit powers of v_1, v_3, v_4, and v_5 are different, causing different interference. If we select Fig. 2b as the optimal

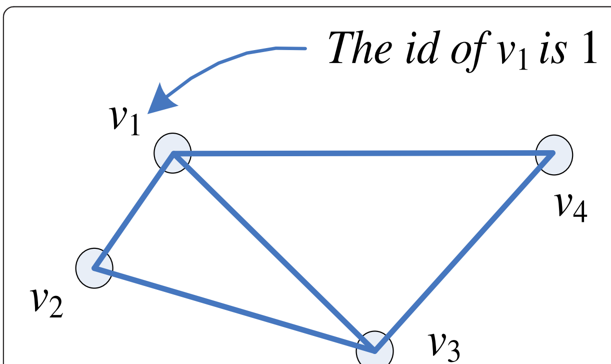

Fig. 1 Description of the *id* of nodes

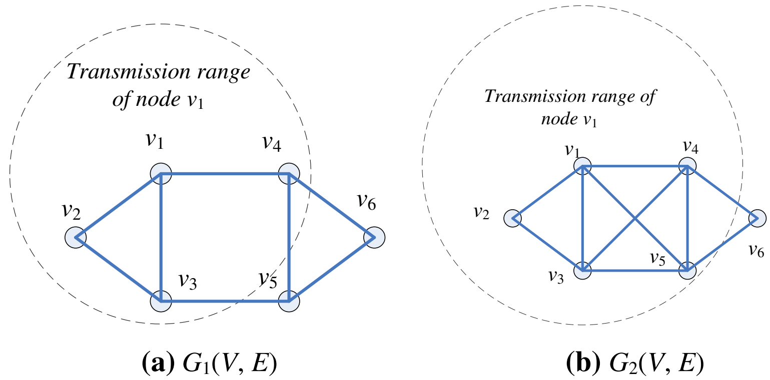

Fig. 2 Interference analysis of different 2-connected network topology

topology, then the link interference between v_1 and v_5 is stronger than that of Fig. 2a. Thus, for k-connectivity requirement, it is a coarse-grained fault-tolerant constraint, i.e., k-connectivity may not meet specific fault-tolerant requirement. In some cases, there are different fault-tolerant requirements between two nodes. Taking a 6-node network as an example, when the fault-tolerance for v_1, v_4, v_3, and v_5 is 3-connectivity and the fault-tolerance between v_2 and v_6 is 2-connectivity, then the topology in Fig. 3 both work, while with different performance.

As mentioned, the k-connectivity requirement may not satisfy specific topology fault tolerance. We thus need to consider different connectivity requirement for any two node pair. We use k_{ij} connectivity between any two nodes to measure the specific fault tolerance.

We define k_{ij} connectivity as fault-tolerant requirement between v_i and v_j. Then, the fault-tolerant constraint $N_{ft}(v_i,v_j)$ is

$$N_{ft}\left(v_i, v_j\right) \geq k_{i,j} \qquad \left(i, j \in V, i \neq j, 1 \leq k_{i,j} \leq k_{ij}(\max)\right) \quad (5)$$

In a fully connected network with n nodes, there are n-1 disjoint paths between any two nodes. Thus, $k_{ij}(\max)$ is n-1.

Furthermore, the optimization objective of network generally is to maximize the network capacity. Since the interference level is the important factor of affecting network capacity. As we know, radio channel capacity decreases as the wanted signal carrier power to interference ratio (C/I) decreases. The expected values of C/I also determine network capacity and data throughput per node [33]. Therefore, the optimization problem of topology control with fault-tolerant constraints for WMNs can be defined as

$$\min \cdot \max\left\{LIS\left(v_i, v_j\right), v_i \in V(G), v_j \in ND(v_i)\right\} \quad (6)$$

subject to :

$$N_{ft}\left(v_i, v_j\right) \geq k_{i,j} \qquad \left(i, j \in V, i \neq j, 1 \leq k_{i,j} \leq k_{ij}(\max)\right) \quad (7)$$

The objective (6) is to minimize the maximum link interference, where $ND(v_i)$ denotes the neighboring set of v_i. Fault-tolerant constraints in (7) emphasize the topology requirement between a specified node pair, which provides the flexibility for topology fault-tolerant requirement, and k_{ij} is the value of specific fault-tolerant requirement.

4 Fault-tolerance-and-interference-aware topology control

4.1 Description of FICTC algorithm

In this section, we present the proposed algorithm, fault-tolerance-and-interference-aware topology control (FICTC). Before providing the FICTC, we first introduce the idea of FICTC and then describe in detail the procedure of FICTC.

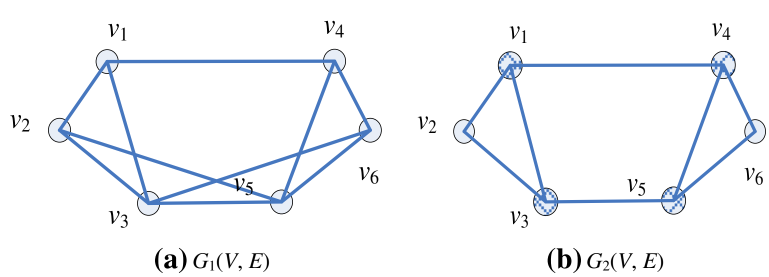

Fig. 3 Interference analysis of different 2-connected network topology

According to Section 4, our optimization objective is to minimize the maximum of link interference $LIS(v_i, v_j)$ under topology fault-tolerant requirement $N_{ft}(v_i,v_j) > k_{ij}$ for any two different node pair, i.e., our proposed topology control not only considers the link interference but also considers the different fault-tolerance requirement for any two node pair in topology.

In order to achieve the different fault-tolerance requirement for any two node pair, according to Menger's theorem in [34], the k_{ij} connectivity between node v_i and v_j is equivalent to having k_{ij} disjoint paths between node v_i and v_j. Therefore, the achievement of k_{ij} connectivity for any two node pair means the solution of k_{ij} disjoint paths for any two node pair, that is, the key issue is how to effectively calculate the disjoint paths. Furthermore, in a process of calculating disjoint paths between any two nodes, the maximum interference in these paths is minimized. According to [34], the number of disjoint paths is equal to that of minimum vertex separation set. Unfortunately, there are no solutions to the number of minimum vertex separation set in a given graph. By the splitting operation of each node, the minimum vertex separation set is obtained via solving the minimum edge cut set. Then, according to max-flow min-cut, the minimum edge cut set can be solved by maximizing the integral flow in a unit capacity network. For a *k*-node-disjoint paths problem, a unit capacity network is obtained by the node-splitting technique from the original network. In order to guarantee minimized maximum link interference for each node, we use Prim's minimum spanning tree algorithm to obtain the node-disjoint paths. In this context, the specific steps for our proposed FICTC are described in Algorithm 1.

In Algorithm 1, the procedure in FICTC has five phases, namely, setting the fault-tolerant requirement k_{ij}, splitting operation, finding an augment path, updating link capacity on augment path, and merging the augment path into the output topology. The procedure of finding an augment path is computed repeatedly until the number of disjoint paths between any two different nodes meets fault-tolerant requirement of the k_{ij} connectivity between any two different nodes. Detailed descriptions are as follows:

1) Setting the fault-tolerant requirement of k_{ij} connectivity
   According the above description, we know the fault-tolerant requirement of k_{ij} connectivity is equivalent to the solution of k_{ij} disjoint paths between any two nodes. Therefore, the following phases will define the k_{ij} disjoint paths between any two nodes as constraint condition.

2) Splitting operation
   As shown in Fig. 4, each node v_i is replaced with v_i" and v_i'. Meanwhile, the link of $e = (v_i, v_{j\cdot})$ is two direct links $e' = (v_1", v_2')$ and $e" = (v_2", v_1')$. The direct links (v_i'- > v_i"), (v_i"- > v_j'), and (v_j"- > v_i') have two weight values, which respectively are the unit capacity and the value of link interference, that is, (c, LIS). For example, in Fig. 4, the $c(v_1', v_1")$, $c(v_2', v_2")$, $c(v_1", v_2')$, and $c(v_2", v_1')$ are set to 1. Furthermore, the value of $LIS(v_1', v_1")$ and $LIS(v_2', v_2")$ are set to 0. The value of $LIS(v_1", v_2')$ and $LIS(v_2", v_1')$ are both 8. In addition, $c(v_1", v_2') = 1$ denotes the direct of link $v_1" \rightarrow v_2'$.

3) Finding an augment path
   Finding the augment path is a key step in obtaining k_{ij} node-disjoint paths. As showed in Fig. 4, the augment path is marked by a dotted line. Specifically, in Fig. 4, the source and destination are, respectively, v_1 and v_9. As long as v_9 is selected as a node in the minimum spanning tree (MST) found based on the links weight $LIS(G)$, the calculation of the augment path is achieved, and the algorithm enters next step.

4) Updating link capacity on augment path
   After calculating the augment path, the unit capacity of directed link is updated. For example, in Fig. 5, for the link (v_1", v_5'), $c(v_1", v_5') = c(v_1",$

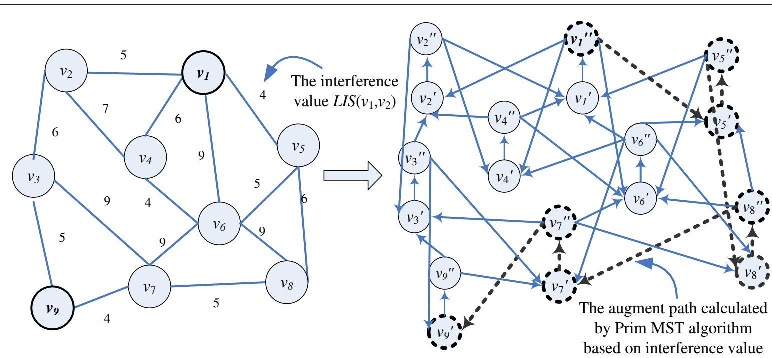

Fig. 4 Example of calculating the augment paths

v_5')-1 = 0, and $c(v_5',v_1'') = c(v_5',v_1'') + 1 = 1$, the link changes to the reverse direction. The other links on the augment path execute the same operation.

5) Merging the augment path to the output topology
When the number of augment paths is not less than k_{ij}, the disjoint paths between v_i and v_j are found. In this context, we need to merger the augment path into the output topology. As shown in Fig. 6, the two augment paths between v_1 and v_8 are added into the output topology.
Main procedure is summarized in Algorithm 1.

4.2 Theoretical analysis of the proposed FICTC

To identify the theoretical performance of FICTC, we present some theorems to prove the performance.

4.2.0.1 Theorem 1 *Give a network G(V,E), let v_x,$v_y$as two different nodes in G(V,E) the min-edge-cut set between $v_x$and $v_y$is equivalent to the maximum integer flow in unit capacity network.*

4.2.0.2 *Proof* From max-flow min-cut theorem, the maximum flow between v_x and v_y is equal to the sum

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Algorithm 1: FICTC

Input: Initial topology $G(V, E)$, links interference matrix $LIS(G)$, k_{ij}.

Output: Topology graph $G'(V',E')$

1. Initial the Visit(v_i, v_j)=0 for all pair (v_i, v_j) in $G(V, E)$
2. Setting the fault-tolerant requirement of of k_{ij} connectivity, i.e., the number of specific disjoint paths k_{ij} between node v_i and v_j
3. Built the directed graph $G_d(V',E')$ by implementing ***splitting operation*** for $G(V, E)$
4. **Repeat**
5. Select node pair (v_i, v_j)$\in G(V,E)$ and set visit(v_i, v_j)=1;
6. Initialization: m=0, PFlag=True, $P_d = \phi$
7. **while** ($m < k_{ij}$ and PFlag=True)
8. **Finding** an augment path P_m using Prim algorithm between v_i and v_j based on $LIS(G)$
9. **If** P is NULL
10. **then** PFlag=False;
11. **else**
12. **Update** $c(v_i'', v_j') = c(v_i'', v_j')-1$ and $c(v_j', v_i'') = c(v_j', v_i'')+1$
13. **end if**
14. $m=m+1$;
15. **End while**
16. **Merge** all links of the m augment paths into $G'(V', E')$
17. **Until** all node pair Visit(v_i, v_j)=1

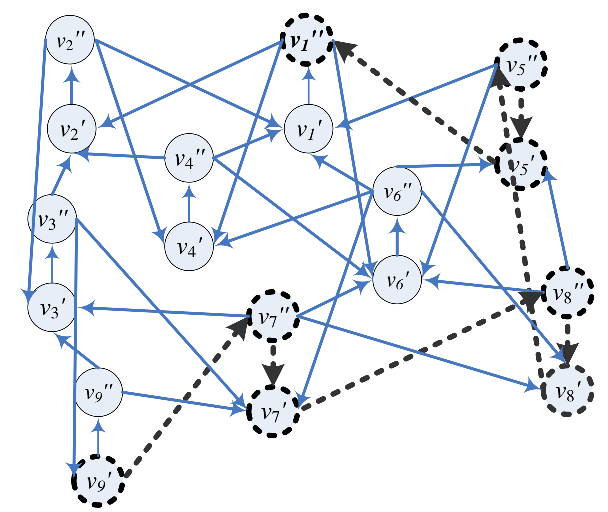


Fig. 5 Example of updating the capacity of link

capacity of the minimum cut edge set. In addition, the maximum capacity is equal to the number of the minimum cut edge set, when the network is with unit capacity. In a unit capacity network, the capacity of each edge is 1; hence, the min-cut set between v_x and v_y is equivalent to the maximum integer flow in a unit capacity network.

4.2.0.3 Theorem 2 *Given a network G(V,E), let v_x,v_y as two different nodes in G(V,E) the number of node-disjoint paths is equal to the maximum integer flow in a unit capacity network obtained by the node-splitting technique.*

4.2.0.4 *Proof* From Menger's theorem [34], the number of node-disjoint paths between any two nodes is equal to that of minimum vertex separation. Since the network is unit capacity obtained by node-splitting, the number of minimum vertex separation is equal to the minimum edge cut set obtained via Theorem1. Thus, we prove the theorem.

4.2.0.5 Theorem 3 *Given an initial network G(V,E), the maximum link interference of the topology $G_d(V',E')$ constructed by the proposed FICTC is minimized.*

4.2.0.6 *Proof* Suppose *G*(*V*,*E*) meet the fault-tolerant constraint. According Section 6, FICTC achieves the optimal topology via node-disjoint paths set R between any two nodes, which are obtained by Prim's minimum span tree algorithm. If we can prove the link maximum interference in path *P*∈R in $G_d(V',E')$ is minimized, we can conclude that the result is true.

Now, we prove by contradiction that each node-disjoint path *P* in $G_d(V',E')$ is minimized. Let *T* be the minimum span tree and *P* be a augment path between v_x and v_y, where *P*∈*T* and *P*∈R. Assume the link maximum interference in path *P* in $G_d(V',E')$ is not minimized. Then, there exist links *e* and *e*', where $e \in E(T)$, $e' \in E(G\text{-}T)$, $LIS(e') < LIS(e)$, and $LIS(P\text{-}\ e + e') = LIS(P)\ \text{-}LIS(e) + LIS(e') < LIS(P)$. Since *P*∈*T* and there is only one path between any two nodes in *T*, the number of paths between v_x and v_y is 1. Hence, $LIS(T\text{-}\ e + e') = LIS(T)\ \text{-}LIS(e) + LIS(e') < LIS(T)$ leads to a contradiction.

Then, we analyze the computational complexity of FICTC. For a given *G*(*V*,*E*) with *n* nodes and *m* links, we use a adjacency list to store the network graph *G*(*V*,*E*). Consider the gateway node already collects all node information. FICTC mainly includes procedures of splitting operation and seeking the k_{ij} disjoint paths between v_i and v_j. For the procedures of splitting operation, v_i is replaced with v_i' and v_i'' and each link is replaced with two directed link $e' = (v_i'', v_j')$ and $e'' = (v_j'', v_i')$, and the total time complexity is $O(n + m)$. In procedure for seeking the k_{ij} disjoint paths, since the network includes $n(n\text{-}1)/2$ different node pairs, the time of solving k_{ij} node-disjoint paths are $n(n\text{-}1)/2$. For each procedure of solving k_{ij}

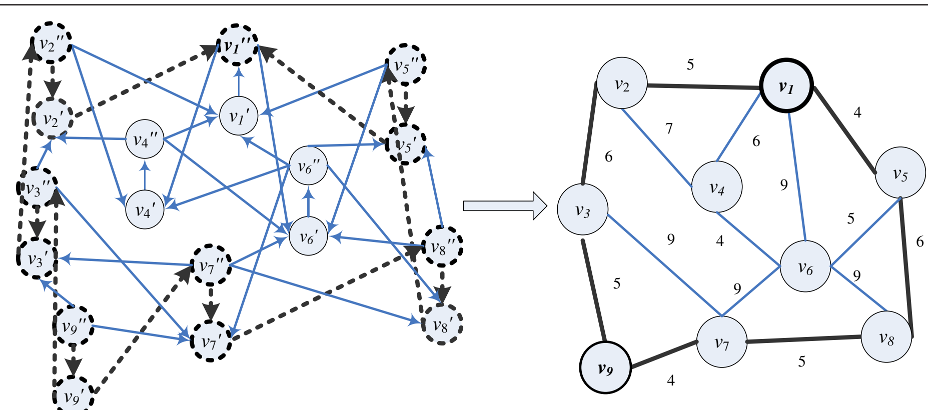


Fig. 6 Example of merging the augment paths

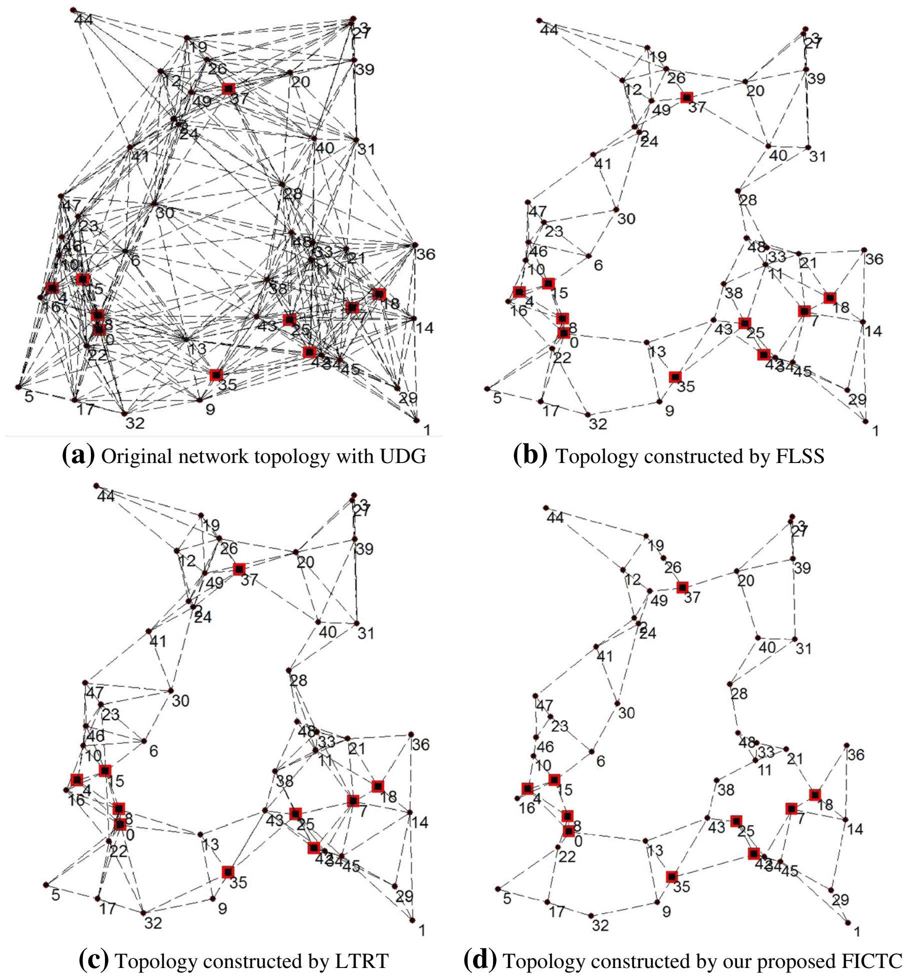


Fig. 7 Topologies constructed by UDG, FLSS, LTRT, and FICTC. **a** Original network topology with UDG. **b** Topology constructed by FLSS. **c** Topology constructed by LTRT. **d** Topology constructed by our proposed FICTC

node-disjoint paths, it needs to compute k_{ij} node-disjoint paths. In the process of computing, an augment path between any two nodes is found by Prim's minimum spanning tree algorithm. If the graph $G(V,E)$ is stored in the adjacency list, the complexity of Prim's minimum spanning tree algorithm is $O(m+n)$. After finding the augment paths, these paths are used to update the flow. The flow updating of each path in worst case take n-1 times addition operation and subtraction operation, then the total time of finding the k_{ij} augment paths is $O(k_{ij}n)$. k_{ij} is various for different node pairs; we thus use $\max(k_{ij})$ to represent it. Therefore, the total computational complexity of FICTC is $O(2n(n\text{-}1)\max(k_{ij})(m+n+k_{ij}n))$.

5 Distributed implementation of the proposed FICTC

In wireless multi-hop network, the practical implementation is generally in a distributed way. In this section, we present the distributed implementation of the proposed FICTC.

The topology of distributed implementation is derived by its neighbor nodes' information of each node. The implementation procedure includes three phases. In first phase, each node v first calculates the interference level $ULIS(v, u)$ based on locally collected neighbor information and the formula (2) in section 3.2. Then, each node sent their the interference level $ULIS(v, u)$ to their neighbor nodes. Finally, according to the formulas (3) and (4), each node calculate the $LIS(u, v)$ based on $ULIS(u, v)$ and the received $ULIS(v, u)$ from their neighbor nodes. In second phase, according to the k_{ij} connectivity fault-tolerant requirement, the k_{ij} disjoint paths between any two nodes pair are required to be solved in disturbed way. Therefore, in the process of solving k_{ij} disjoint paths, the augment path is achieved based on distributed minimum spanning tree (MST) algorithm [35]. In the final phase, these links that included in all augment paths are merged into the constructed topology. The detailed procedure is summarized in Algorithm 2.

Algorithm 2: The distributed algorithm of FICTC

Phase 1:

1. Each node v_i calculates the interference value $ULIS(v_i, v_j)$ based on locally collected neighbor information and the formula (2) and broadcast the message of the interference value .

2. Each sensor node v_i receives a broadcast message with the interference value form neighbor nodes $N(v_i)$.

3. Each node calculates the $LIS(u, v)$ based on broadcast message with the interference value.

Phase 2:

1. **While** each node v_i established the store of augment path information for node pair (v_s, v_t)$\in G(V,E)$, and selects a neighbor node with minimum $LIS(v_i, v_j)$, $v_j \in N(v_i)$ and sent a message of constructing augment path based on distributed minimum spanning tree (MST) algorithm.

2. **If** each node v_i receives a constructed message from its neighbor node v_j , **then**

3. **If** $(L_j(s_k) + LIS(v_i, v_j)) < L_i(s_k)$ **then** updating the parent node $PN(s_k, j)=i$, where s_k denotes the source of node pair, $L_i(s_k)$denotes the sum of interference value between source s_k and v_i.

4. **If** $v_i == t_k$ **then** node v_i sents a reverse constructed message of augment path to the parent node.

5. **If** node v_i receives a reverse constructed message, **then**

6. Node v_i updating the transmission power according to the maximum the $LIS(v_i, v_j)$ in all augment paths.

7. **If** the number of augment paths for each node pair(v_i, v_j) is more than or equal to the k_{ij}, **then** end

8. **End while**

6 Performance evaluation

First, we take an example to detail FICTC and compare with other *k*-connected algorithms, such as FLSS and LTRT. Consider a network with 50 nodes randomly placed in a 1000 m × 1000 m field; transmit range of all nodes is 250 m. We randomly generate 10 nodes and assume that the fault-tolerant constraints k_{ij} among them are 3, and that among others nodes are 2, i.e., $N_{fl}(v_i,v_j) \geq 3$, $i,j \in \{0,4,7,8,15,18,25,35,37,43\}$, $i \neq j$, and $N_{ft}(v_{i'},v_{j'}) \geq 2$, $i',j' \in \{V\text{-}\{0,4,7,8,15,18,25,35,37,43\}\}$, $i' \neq j'$. The topologies constructed by UDG, FLSS, LTRT, and FICTC are respectively shown in Fig. 7a–d.

From Fig. 7, Fig. 7a is original topology constructed by unit disk graph (UDG), i.e., unit disk graph is a network topology derived by using the maximum the transmission radius of 250 m. In Fig. 7b, the topology constructed by the FLSS algorithm. This algorithm first sorts all edges in ascending order of weight, then judges the *k*-connected between two terminate nodes of each edge in the order. If it is *k*-connected, the edge is inserted into output topology graph G_k. For the topology derived by LTRT in the Fig. 7(c), the LTRT algorithm is a topology control algorithm combining two different algorithms, TRT and LMST. TRT is basically an algorithm

Table 1 Simulation parameters setting

The number of nodes(N)	Number of the first group nodes	Number of the second group nodes	The k_{ij} connectivity between two nodes		The corresponding k connectivity degree of meeting k_{ij} connectivity of two group nodes for the FLSS and LTRT algorithms
			The first group nodes	The second group nodes	
50 to 100	N/10	N-N/10	2	3	3

to efficiently construct 2-edge connected topologies. However, it can be extended for constructing k-edge connected networks by just recursively repeating the same procedures. The topology constructed by our proposed FICTC is shown in Fig. 7d. In Fig. 7, our proposed FICTC shows the number of disjoint paths between any node pair in 10 nodes {0,4,7,8,15,18,25,35,37,43} is 3, while others are 2, showing the constructed topology satisfies the specific fault-tolerant requirement k_{ij}. Furthermore, we can easily know from Fig. 7, the FICTC present smaller transmit radius and node degree than FLSS and LTRT. The performance of FLSS is better than LTRT.

Then, in order to show the validation of our proposed algorithm, we consider a network with 50 to 100 nodes randomly placed in a 1000 m × 1000 m field. Transmission range of all nodes is 250 m. Table 1 lists the fault-tolerant requirement. The nodes are divided into two groups. We compare our FICTC with FLSS and LTRT. The graph parameters of comparison among FLSS, LTRT, and FICTC include node degree and transmit radius. The node degree is referred as the number of nodes within the transmission radius of a node. Figures 8, 9, and 10 demonstrate a comparison among these topology control algorithms. Here, the NONE denotes the original topology constructed by UDG in Figs. 8, 9, and 10.

Figure 8 shows the average node degree of the topologies derived by FLSS, LTRT, FICTC, and NONE. The NONE in Fig. 8 is defined as the network topology derived by using the maximum transmit radius. The node degree of NONE linearly increases with the number of nodes, while node degrees of FLSS, LTRT, and FICTC are almost constant. Meanwhile, the average node degree of FICTC is smaller than other algorithms. In Fig. 8b, the average transmit radius of FICTC is smaller than FLSS, LTRT, and NONE, indicating better network performance in terms of interference.

But, as we know from [32], the minimum node degree does not imply the minimum interference. In order to further validate the performance of total interference, we evaluate the performance of our proposed algorithms in above random network using the interference metric in section 3.2. In Fig. 9, we plot respectively the maximum links interference and average links interference for a varying number of nodes.

Figure 9 shows FICTC and distributed FICTC enjoy better maximum link interference performance over FLSS, LTRT, and NONE. Meanwhile, in Fig. 9b, the average link interference of FICTC is weaker than NONE, LTRT, and FLSS. Since FICTC considers the interference metric as link cost, thus we can achieve the minimal of maximum interference.

Then, we evaluate the average expended energy ratio (EER), where is defined in [13, 14]. The definition is as follows.

$$EER = E_{\mathrm{AVE}} \div E_{\mathrm{MAX}} \times 100[\%] \tag{8}$$

In (8), the E_{AVE} denotes the average transmission power over all the nodes, and E_{MAX} is the maximal transmission power. We compare the EER performance

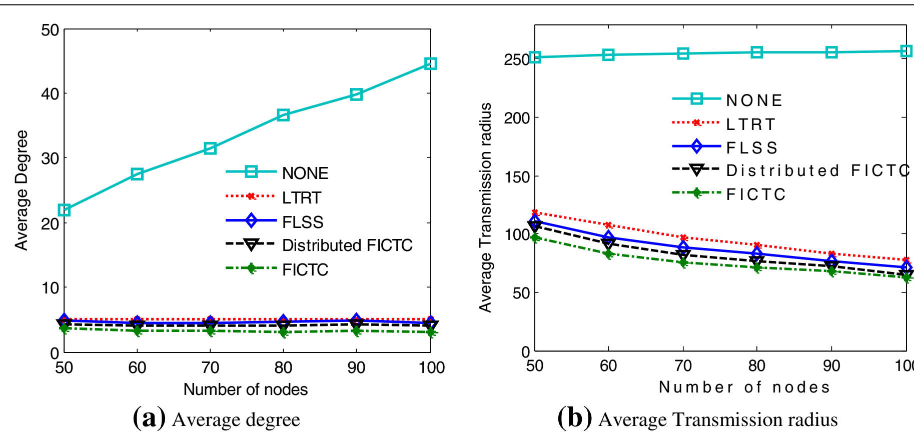
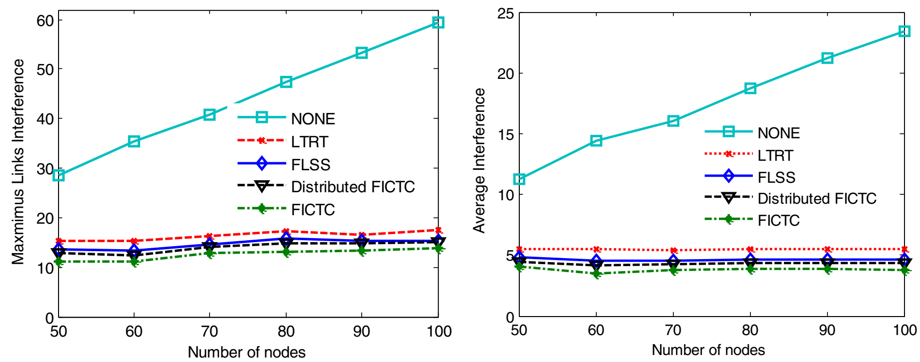


Fig. 8 Comparison of average node degree and average transmission radius. **a** Average degree. **b** Average transmission radius



(a) Maximum links interference **(b)** Average links interference

Fig. 9 Comparison of maximum links interference and average links interference. **a** Maximum links interference. **b** Average links interference

of our FICTC with FLSS and LTRT. The result of performance is shown in Fig. 10.

In Fig. 10, we know the proposed FICTC and distributed FICTC both performs better than other algorithms and the difference of performance reduce with the increase of the number of nodes.

In order to fully understand FICTC, we evaluate the performance of different algorithms by ns-2 simulations. The parameters are shown in Table 2. We utilize UDP connection and constant bit rate (CBR) flow for each pair. The length of packet is 512 bytes and the sending rate of each CBR flow is fixed at 2 Mbps. All transmissions are unicast following the 802.11 MAC protocol. The routing scheme is AODV for MCMR-WMN. As for the fault-tolerant requirements, we use UDG, FLSS, LTRT, distributed FICTC, and FICTC. We compare the performance by measuring the throughput and average E2E delay.

Figure 11 shows that the throughput of FICTC and distributed FICTC are higher than NONE, LTRT, and FLSS; meanwhile, its average E2E delay is the lowest. Unlike FLSS and LTRT, FICTC not only considers the length of the shortest path, but also uses the link interference as link weight in solving the topology. Importantly, only FICTC achieves the fault-tolerant constraint between any two nodes.

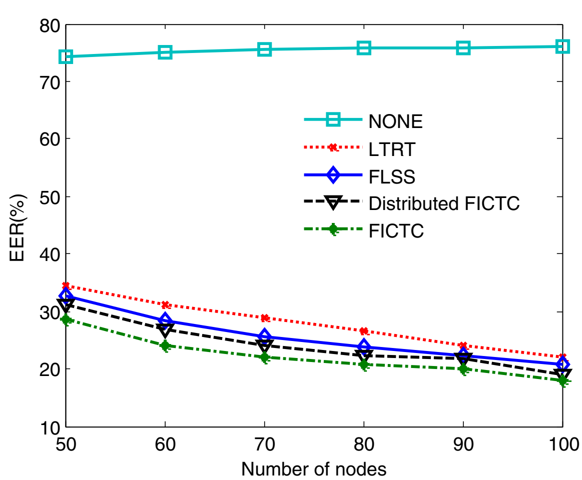


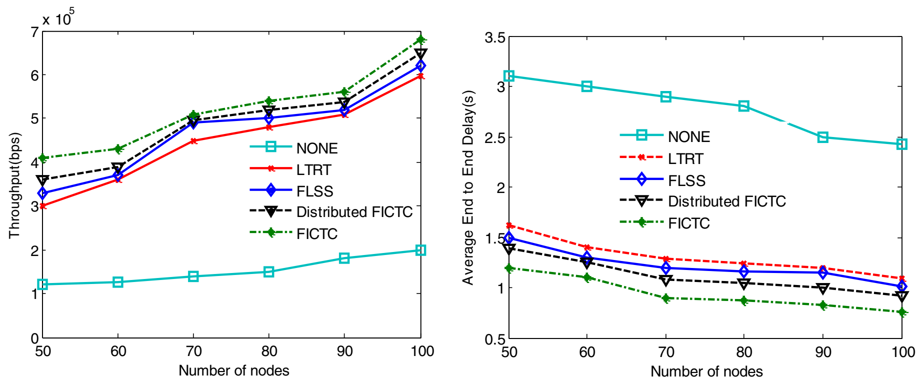
Fig. 10 Expended energy ratio

7 Conclusions

In this work, topology optimization of considering the fault tolerance and network interference in WNMs was investigated. We proposed a fault-tolerance-and-interference-aware topology control (FICTC) algorithm for WNMs. We first analyzed the network performance under the requirement of k-connectivity. Then, the interference model and the problem formulation of improving the network performance for k-connectivity topology were presented. By the analysis of FICTC algorithm, we proved that FICTC not only meets the fault-tolerant requirement, but also minimizes the maximum node interference. Moreover, the distributed implementation of the proposed FICTC was proposed. The proposed FICTC algorithm plays an important role for improving network and fault tolerance performance in WNMs. We integrate the disjoint paths between any

Table 2 Simulation parameters

Field size	1000 m × 1000 m
Maximum transmission range	250 m
Interference range	550 m
Number of nodes	50–100
MAC protocol	802.11
Traffic pattern	CBR
Trans. protocol	UDP
Routing protocol	AODV
Length of packet	512 bytes



(a) Throughput **(b)** End to End delay

Fig. 11 Performances comparison of RICRC, UDG, LTRT, and FLSS. **a** Throughput. **b** end-to-end delay

two nodes into topology optimization with fault tolerance requirement. For different fault tolerance requirement, graph-based simulations results indicated that FICTC outperforms the state-of-the-art fault-tolerant topology control algorithms in terms of average node degree, maximum transmit radius, and maximum link interference. Furthermore, the ns-2 simulations showed FICTC achieves higher throughput and lower E2E delay. In term of energy consumption, we use the average expended energy ratio (EER) to evaluate the energy performance of our proposed FICTC. The result indicated the proposed FICTC achieve lower EER than other algorithms. These results demonstrate that the proposed solutions are promising for specific fault-tolerant requirement in practical network deployment. However, There are several problems for further research on fault-tolerance-and-interference-aware topology control. The proposed FICTC does not analyze the network performance of considering sophisticated model for the radio signal propagation. Moreover, the FICTC algorithm needs to deal with mobile WNMs. In future study, we plan to investigate the network performance for these problems.

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Competing interests

The authors declare that they have no competing interests.

Authors' information

Xuecai Bao received Ph.D. degree from school of electronics and information engineering at Harbin Institute of Technology, Harbin, People's Republic of China. He is currently a lecturer in the Jiangxi Province Key Laboratory of Water Information Cooperative Sensing and Intelligent Processing, Nanchang Institute of Technology, Nanchang. His research interests include resource management for wireless mesh networks, wireless ad hoc networks, and wireless sensor network.

Chengzhi Deng received the M.S.c degree in Optics from Jiangxi Normal University, Nanchang, China, in 2005, and the Ph.D degree in information and communication engineering from Huazhong University Science and Technology, Wuhan, China in 2008. He is currently a professor in the Jiangxi Province Key Laboratory of Water Information Cooperative Sensing and Intelligent Processing, Nanchang Institute of Technology, Nanchang. His major research interests focus on wireless sensor network, image reconstruction, and remote sensing image processing.

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