Journal of Network Intelligence ©2017 ISSN 2414-8105 (Online)
Taiwan Ubiquitous Information Volume **2**, Number **4**, November **2017**

Topology Optimization of Fault Tolerant Target Monitoring for Energy Harvesting Wireless Sensor Network

Xuecai Bao, Chengzhi Deng, Zhuhan Liu, Longzhe Han

Jiangxi Province Key Laboratory of Water Information Cooperative Sensing and Intelligent Processing
Nanchang Institute of Technology
No.289, Tiangxiang Road, Nanchang, Jiangxi, 330099, China
lx97821@126.com, dengchengzhi@126.com, lzh512@nit.edu.cn, lzhan@nit.edu.cn

Received June 2017; revised November 2017

Abstract. *Energy harvesting wireless sensor network (EH-WSN) is a promising solution for near-perpetual environmental monitoring. However, the failure of senor node in EH-WSN has a strong impact on the quality of the environmental monitoring. In this paper, we focus on the topology optimization of fault tolerant target monitoring for EH-WSN. We first describe the fault tolerant requirement of target monitoring and formulate the topology optimization problem. Then, the topology optimization algorithm of fault tolerant target monitoring (TFTTM)is proposed. Based on link weight of energy-efficient, the proposed algorithm achieves the minimum of maximum energy consumption on sensor nodes by the calculation of disjoint paths between sink node and other nodes. Expensive simulations show that the proposed algorithm obtains less average node degree and average path length under the same requirement. Moreover, the proposed algorithm achieves longer network lifetime than existing fault tolerant topology control algorithms.*
Keywords: Energy harvesting wireless sensor network, Fault tolerant target monitoring, Topology control

1. **Introduction.** A wireless sensor network (WSN) is composed of group of sensor nodes that are widely deployed for environmental sensing, natural disaster relief and military target tracking. Due to limitation of energy supply in WSN, the main research problem focuses on the energy allocation, that is, each node adjusts its power to prolong lifetime in process of wireless communication. Topology control in WSN is an important issue, the main aim of which is to save energy, reduce interference among nodes and extend lifetime of the network [1, 2]. Considerable state-of-the-art topology control algorithms are proposed. Typically, these methods can be categorized as minimum interference and minimum transmission power with maintaining the network connectivity. Most of existing topology optimization algorithms mainly focus on the WSN based on battery energy supply [3, 4]. However, manual recharging or replacement of batteries is not practical.

Recently, energy harvesting technologies, such as solar, wind, vibration and so on, have been used to solve the energy constraint in the WSN. This type of WSN generally called energy harvesting WSN(EH-WSN). In EH-WSN, the objective of design mainly focuses on the performance optimization based on ensuring near-perpetual lifetime of network. As we know, the energy availability varies with change of environment, which affects transmission power of node in different times. Therefore, the design of topology control in EH-WSN depends on energy resources in energy harvesting system. Fortunately, the solar energy is uncontrollable but predictable [5]. Several energy prediction methods have been proposed based on different energy-harvesting WSNs. Therefore, the existing topology optimization algorithms of EH-WSN generally integrate with energy prediction methods [6, 7, 8]. However, these algorithms mainly focus on the optimization of network topology composed of sensor nodes and do not consider the fault tolerant of target monitoring.

In this paper, we focus on the topology optimization problem of fault tolerant target monitoring for energy harvesting WSN. The goal is to ensure that each target is monitored by at least k sensor nodes and is k-connected to sink node based on energy prediction. So far, most existing topology control algorithms focus on conventional battery-operated WSN, their optimization objective is to minimize the interference or transmission power. However, our objective is to minimize of maximizing energy consumption under the condition of guarantying each target monitored by k sensor node. Our major contributions are summarized as follows

(1) We illustrated the relationship between topology optimization and fault tolerant target monitoring. Furthermore, we give the analysis of minimizing the maximum node energy consumption.

(2) We proposed a heuristics topology optimization algorithm based on the solar harvesting energy, which achieve the maximum network lifetime under the condition of guarantying each target monitored by k sensor nodes.

(3) The extensive simulation results demonstrate the performance delivered by the proposed algorithms can improve the monitoring quality and extend the network lifetime effectively.

The rest of the paper is organized as follows. Section 2 presents related work. Section 3 descripts energy prediction model and problem description, respectively. Section 4 presents topology optimization algorithm for fault tolerant target monitoring. In Section 5, we evaluate the proposed algorithm performance, followed by concluding remarks in Section 6.

2. **Related Work.** Fault tolerant topology control problems in conventional sensor network based on battery energy supply have been extensively studied [9]. Typically, these fault tolerant topology control algorithms generally focus on constructing k-connected topologies [9, 10, 11, 12, 13, 14]. In [10], the authors provided a preserving k-connectivity topology control algorithm. The algorithm analyzes the relationship between k-connectivity and node degree, but the literature doesnt́ present the minimum node degree. Wang et al. [11] proposed a construction method RESP of fault tolerance sparse topologies and demonstrated the proposed RESP can prolong the network lifetime. L. Li et al. [12] proposed k-connectivity topology control algorithm. In the algorithm, each node needs to link at least one node in every cone of degree a centered at this node. Meanwhile, they proved that it could 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. Miyao et al. [14] proposed a Local Tree-based Reliable Topology (LTRT) algorithm, but the LTRT only constructed a k-edge connectivity with lower time complexity. Guo et al. [15] studied a scheme based on cooperative communication to achieve 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. In energy harvesting WSN, Dong et al. [16] introduced a scheme that constructs and maintains a fault-tolerant wireless sensor network topology. But, this scheme mainly constructs a k-connected backbone of energy-rich nodes. Yin et al. [17]proposed fault-tolerant topology design problem for an

energy-harvesting heterogeneous WSN. In literature of Yin et al. [18], six different algorithms were proposed to solve the fault tolerant topology control problem and the results show that the proposed methods could save up to around 80% costs.

The above mentioned algorithms can construct k-connected topology with high energy-efficiency, but most of them do not both consider the fault tolerant of target monitoring and topology. We focus on the fault topology design of target monitoring in energy harvesting WSN through graph-based theory.

3. Related Model, Problem Description and Formulation.

3.1. Network model. We consider an energy harvesting WSN $G(V \cup Z \cup s, E)$, where $V = \{v_1, v_2, \cdots, v_i, v_{i+1}, \cdots, v_n\}$ is the set of n sensor nodes, $Z = \{z_1, z_2, \cdots, z_i, z_{i+1}, \cdots, z_m\}$ is the set of monitoring targets, s is the sink node, and $E = \{e_{ij}\}$ is the set of all edges. Each sensor node $v_i \in V$ is powered by solar energy source and has a fixed maximum transmission and monitoring range. The sensor node $v_i \in V$ is deployed for periodic environmental monitoring. For each sensor node, the $EC^t(v_i)$ represents the energy consumption of sensor node v_i at time slot t, $0 < t < L$. $SE(v_i)$ denotes the sum of energy consumption of sensor node v_i in total L time slots. $BE(v_i)$ denotes the battery capacity of sensor node v_i.

3.2. Energy harvesting model. In this paper, we mainly consider the environmental monitoring. For the long-period monitoring task, the number of monitoring each target is determined by the collected energy. Therefore, the consumption energy of each sensor node is less than the harvesting energy. We take the solar-powered as the energy supply and use a widely adopted environmental energy harvesting assumption, i.e., the harvesting energy of each sensor node in a future time period is uncontrollable but predictable by its historic energy harvesting profile. Further, we assume that time period is divided into L time slots after which the next recharging pattern will be repeated [6]. Many prediction approaches of harvesting energy are provided [6, 7, 8]. We take the widely used energy prediction algorithm, i.e. Exponentially Weighted Moving-Average (EWMA) algorithm [7]. The specific formulation of energy prediction is as following.

$$\overline{HE}(t) = w\overline{HE}(t-T) + (1-w)\overline{HE}(t-T) \quad (1)$$

In (1), the w denotes the given weight $(0 < w < L)$ and the $HE(t)$ denotes the prediction of the amount of harvested energy at time slot t. The $HE(t-T)$ is the actual amount of energy harvested at time slot $t-T$. According to the above formulation of energy prediction, the amount of energy for sensor node $v_i \in V$ in next L time slots is defined as

$$SE(v_i) = min\{BE(v_i), RE(v_i) + \sum_{t=1}^{L} \overline{HE}(t)\} \quad (2)$$

In (2), the $BE(v_i)$ is the battery capacity and the $RE(v_i)$ is the residual energy of sensor node v_i at current time slot t.

3.3. Problem description and formulation. In this section, we first describe the relationship between topology optimization and fault tolerant target monitoring. Then, we define the topology optimization problems.

Topology optimization is one of the key problems for improving the capacity and reliability. In the environmental monitoring WSN, the reliability of monitoring is one of the fundamental considerations. The reliability requirement of WSN topology for environmental monitoring mainly includes two aspects, i.e. fault tolerant of network composed of sensor nodes and fault tolerant of target monitoring, which also generally consider each target is monitored by k sensor nodes. For WSN, as we know, the fault tolerant mainly indicates that the network or target monitoring still maintains the state of normal working when one or several sensor nodes are failure. For example, in Fig.1, two targets are both monitored two sensor node simultaneously. When one sensor is failure, the target monitoring doesnt́ have any impact. So, we believe that the topology in Fig.1 has fault tolerant capability against failure of one sensor. In Fig.2, the network not only is provided with the fault tolerant of target monitoring, but also has the fault tolerant of topology, i.e. it exists a path between each sensor node and the sink node when any one sensor node suffer from a failure. The network is also called 2-connectivity topology.

In this paper, the topology optimization objective is to construct a fault tolerant topology network, which is similar to the fault tolerant topology in Fig.2. However, the optimization does not just consider the failure of one sensor node, but the problem for the failure of k-1 sensor nodes. Therefore, the key is that how to establish the problem formulation. According to Mengerś theorem [18], the construction of k-connected topology can be solved by calculating disjoint paths between any two sensor nodes. Similarly, as we can see from Fig.2, the 2-connected topology means that it has two disjoint paths between senor node and sink node. So, we replace the problem of fault tolerant of topology and target monitoring with the solution of node disjoint paths. According to the requirement of fault tolerant, we divide the calculation of disjoint paths into two aspects. The first aspect is the calculation of disjoint paths between target nodes and sink node. The second aspect is the solution of disjoint paths between sensor nodes and sink.

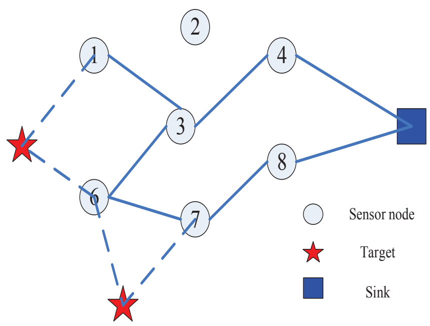


FIGURE 1. Fault tolerant of target monitoring

From above problem description, the optimization problem and the ideal of achieving the fault tolerant target monitoring are presented. Then, we define the problem formulation. Since the environmental monitoring not only require the extending of network lifetime, but also enhance the target monitoring reliability. Therefore, our purpose is to minimize maximum node energy consumption of under the condition of fault tolerant of target monitoring and topology. To this end, the problem formulation is defined as

$$Min \cdot max(Ec(v_i)) \qquad 1 \leq i \leq n \tag{3}$$

$$subject\ to: \tag{4}$$

$$M(z_j) \geq k \qquad 1 \leq j \leq n \tag{5}$$

$$DP(z_j, Sink) \geq k \qquad 1 \leq j \leq n \tag{6}$$

$$DP(v_i, v_j, Sink) \geq k \qquad 1 \leq i \leq n, \geq 1 \leq j \leq n \tag{7}$$

$$Ec(v_i) < SE(v_i) \tag{8}$$

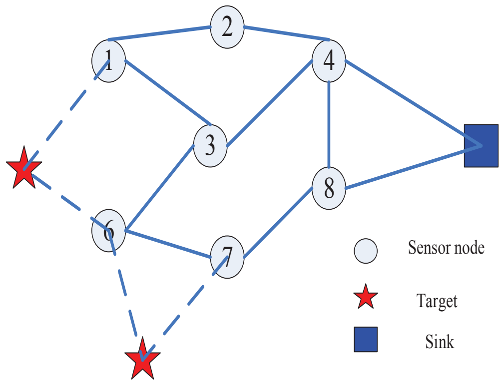


FIGURE 2. Fault tolerant of target monitoring and topology

In (3), the objective is to minimize the maximum node energy consumption, where $Ec(v_i)$ denotes the energy consumption of v_i. The target z_i is monitored by k sensor nodes in (4). The $DP(z_j, Sink)$ emphasizes the number of disjoint paths is at least k between target nodes and sink node. Moreover, the $DP(v_i, v_j, Sink)$ denotes the disjoint paths between sensor nodes and sink node are more than k, i.e. the fault tolerant between sensor nodes and sink node is k connectivity. In (7), the constraint denotes the consumption energy is less than the harvesting energy.

4. **Topology Optimization Approach.** In this section, we present our solution to the optimization problem described in section 3.3. We first introduce the ideal of topology optimization based on the harvesting energy of each sensor node. Then we present the topology optimization algorithm of fault tolerant target monitoring(TFTTM).

From section 3.3 we know, the problem of fault tolerant target monitoring and topology can convert into the solution of disjoint paths among sensor nodes and between target nodes and sink node. But, in process of calculating the disjoint paths, the energy consumption needs to be considered. Therefore, the proposed optimization algorithm first meets the fault tolerant requirement and then minimizes the maximum sensor node energy consumption. In order to achieve the optimization objective, we first solve the k minimum energy consumption node-disjoint paths between target nodes and sink node. Then we calculate the k minimum energy consumption node-disjoint paths between sensor nodes and sink node based on the harvested energy on each node. The specific procedure is summarized in algorithm 1.

Algorithm 1(TFTTM) :

Input: Initial topology $G(V, E)$, the amount of harvesting energy $SE(v_i), k$
Output: The optimization topology $G(V, E)$
1. Initialization$G'(V', E')$=NULL, P'=NULL
2. Establishing the topology $G_d(V', E')$ of solving the node-disjoint paths from initial topology $G(V, E)$
3. For each target node $z_i \in Z$
4. Solve the k node disjoint paths between z_i and sink node $P(z_i, sink)$ based on link weight $1/w(v_i, v_j) = 1/(SE(v_i) + SE(v_j))$ in $G_d(V', E')$
5. $P' = P' \cup P(z_i, sink)$
6. For each sensor node $v_j \in Z$
7. Solve the k node disjoint paths between v_j and sink node $R(z_i, sink)$ based on link

weight $1/w(v_i, v_j) = 1/(SE(v_i) + SE(v_j))$ in $G_d(V', E')$
8. $P' = P' \cup R(v_j, sink)$
9. Return $G'(V', E') \cup P'$

For the algorithm 1, we take a topology for example to understand the step. First, we establish an initial topology based on the monitoring distance and the maximum transmission distance of sensor node and take it as the input topology. For instance, an initial topology is shown in Fig.3. In line 1 of the algorithm 1, the output topology $G'(V', E')$ and the variable of storing the disjoint paths P' are initialized(in line 1). Then, we need to construct a topology composed of node disjoint paths. According to graph theory, the initial network $G(V, E)$ only can solve the link-disjoint paths and cant calculate the node-disjoint paths. In order to calculate the node-disjoint paths, the new topology $G_d(V', E')$ need to be established based on decomposition Operation of initial topology $G(V, E)$ (line 2). The specific established procedure is as follows. Each Sensor node v_i in $G(V, E)$ is replaced with v_i'' and v_i' and establish a direct link from v_i'' to v_i'. Meanwhile, the link of $e = (v_i, v_j)$ in $G(V, E)$ is two direct links $e' = (v_1'', v_2')$ and $e'' = (v_2'', v_1')$. From max-flow min-cut and Mengers theorem, the calculation disjoint paths between any two different node v_i and v_j is obtained by the maximum integer flow algorithm in new topology $G_d(V', E')$. First, According the harvesting energy $SE(v_i)$ in next L time slots, the k node-disjoint paths between z_i and sink node $P(z_i, sink)$ are solved. In calculation procedure, the disjoint paths is obtained by seeking the augment path with minimum link weight $1/w(v_i, v_j) = 1/(SE(v_i) + SE(v_j))$(line 4). Then, these disjoint paths is merged into the output topology $G'(V', E')$(line 5). Second, the calculation of k node disjoint paths between v_j and sink node $R(z_i, sink)$ is taken the same method above(line 6-8). Finally, the topology composed of all disjoint paths is outputted into $G'(V', E')$. The $G'(V', E')$ is the final optimization topology.

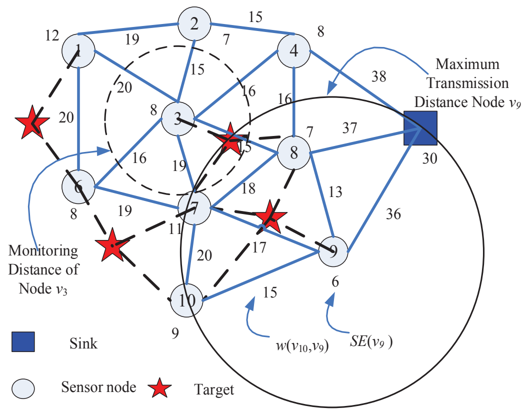


FIGURE 3. Initial topology $G(V, E)$

For example, we take the topology in Fig.3 as initial topology and assume the connectivity value of k is defined as 2. According the calculation of algorithm 1, all disjoint paths P' between target nodes and sink node are showed in Fig.4.

Then, we solve the disjoint paths between sensor nodes and sink node in the same way(line 6-7). These paths $R(v_j, sink)$ are stored into P' by the operation of $P' = P' \cup R(v_j, sink)$(in line 8). The final optimization topology $G'(V', E')$ is showed in Fig.5(in line 9).

The above description is the calculation procedure of algorithm 1. Then we analyze the computational complexity of the proposed algorithm. For a given $G(V, E)$ with n

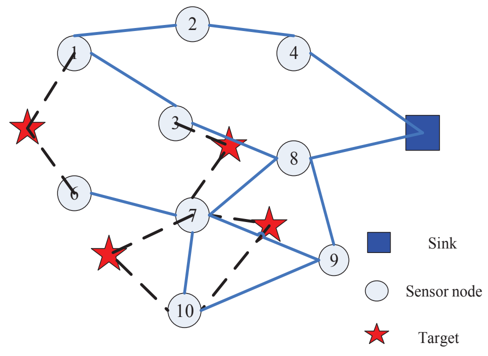


FIGURE 4. Disjoint paths between target nodes and sink node

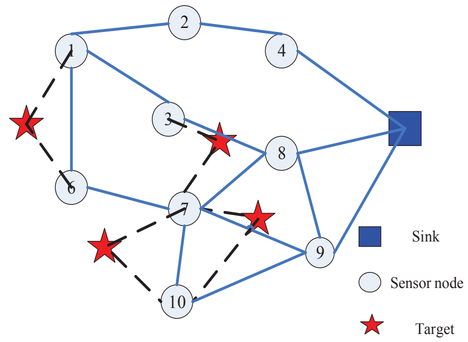
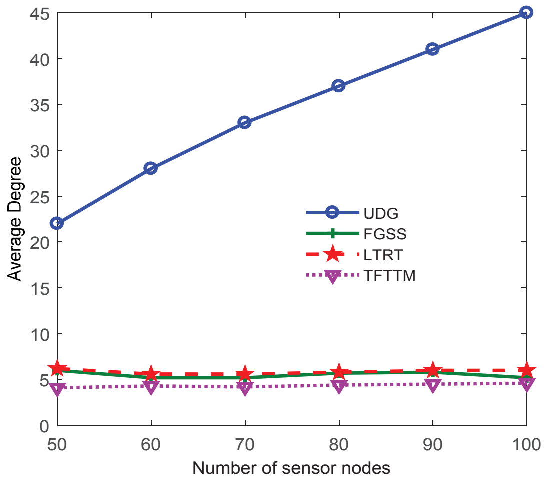
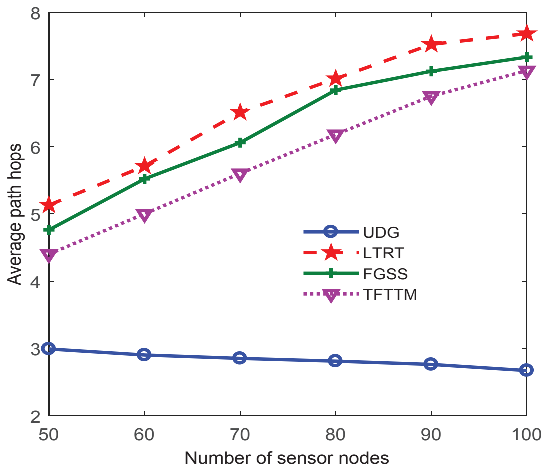


FIGURE 5. Disjoint paths between sensor nodes and sink node

sensor nodes, m target nodes and $l$links. We use an adjacency list to store the network graph $G(V, E)$. First, there are construction procedures of topology $G_d(V', E')$ adapting to the disjoint paths. According to description of above algorithm 1 procedure, the computational complexity of constructing $G_d(V', E')$ is $O(n + l)$. Then, the proposed algorithm mainly includes two aspects. In first aspect, the k disjoint paths between target nodes and sink node are required to solve. In procedure for seeking the k disjoint paths, since the network exists m different sensor node pairs between target nodes and sink node, the number of times for solving k node-disjoint paths is m. For each procedure of solving k node-disjoint paths, the k node-disjoint paths between any two sensor nodes is found by maximum integer flow algorithm. If the graph $G(V, E)$ is stored in the adjacency list, the complexity of is $O(k(l + n))$. The merging operation of k node-disjoint paths in the worst case takes $k(n-1)$ times operation. Therefore, the total computational complexity of first aspect(in line 3-5 in algorithm 1) is $O(mk(l + n) + k(n - 1)))$. Similarly, In second aspect, this aspect mainly solves the k disjoint paths between sensor nodes and sink node, the total computational complexity of second aspect(in line 6-8 in algorithm 1) is $O(nk(l + n) + k(n - 1)))$. The final merging procedure in the worst case takes $k(n - 1)$ times operation. So, the total time complexity of the proposed algorithm is $O((m + n)k(l + n + k(n - 1))$.



(a) Average degree



(b) Average path hops

FIGURE 6. Comparison of average node degree and path hops

5. **Performance Analysis.** First, we verify the proposed TFTTM algorithm via the topology simulation. The major performance include average hops and average node degree, which are the major factors influencing the throughput and delay. We set the same parameter and take the real solar data in literature [19]. We consider networks of 50 to 100 sensor nodes and 10 to 60 target nodes randomly placed in a $1000m \times 1000m$ field. The transmission range of each sensor node is 250m and has a uniform sensing range of 200m. We compare our proposed TFTTM algorithm with the unit disk graph (UDG) and state-of-the-art algorithms which generate k-connected topologies, such as FGSS [13], LTRT [14]. The fault tolerant requirement of topology is to meet the 2-connectivity, i.e. $k = 2$. Fig.6 shows a comparison among these topology control algorithms.

In Fig.6 (a), it shows our proposed TFTTM algorithm has better average node degree performance than FGSS, LTRT, and UDG. Furthermore, Fig.6 (b) also demonstrates the average path hops of proposed TFTTM algorithm are less than UDG, LTRT, and FGSS, which means it will reduce the end-to-end delay from target node to sink node.

In order to validate the performance of the proposed TFTTM algorithm, we evaluate the network lifetime. We consider networks of 50 to 100 nodes and 30 target nodes randomly deploy in a $1000m \times 1000m$ field. The transmission range and sensing range are respectively 250m and 200m. All sensor nodes are equipped with an solar cell and assume the solar cell of each sensor node has a conversion rate of 10% and a recharging efficiency of 50%. We first run the UDG, LTRT, FGSS and TFTTM to construct the topologies and calculate their network lifetime respectively. These algorithms run until sensor nodes fail to monitor a target. We compare these algorithms with different numbers of active sensor nodes and target nodes. For the parameter setting, the 5000 hours are defined as a network lifetime upper bound and at this time, it indicates that the network can operate perpetually. And we assume each sensor node is able to communicate with sink nodes by multiple hops. Moreover, energy consumption of each node on communication paths is the same.

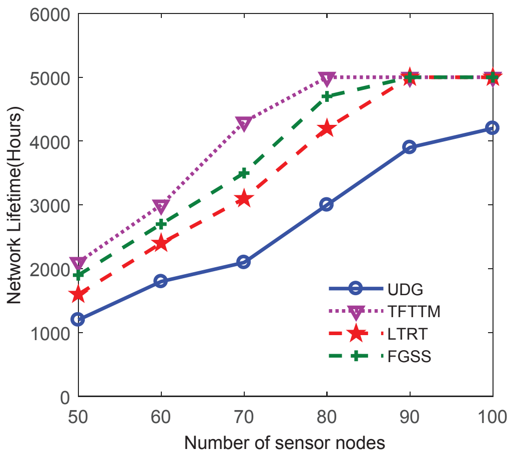


FIGURE 7. Network lifetime of different number of sensor nodes with 30 monitoring targets

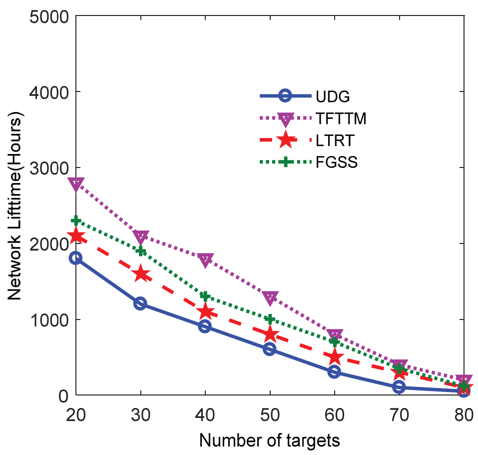


FIGURE 8. Network lifetime of different number of monitoring targets with 50 sensor nodes

From Fig.7 as we know, the network lifetime increases with the increasing of sensor nodes. The reason is that when the number of sensor nodes increases, the average monitoring time of each sensor nodes reduces and has more times to harvest energy. Furthermore, since the number of target nodes is limited to 30, the network exist more transmission path to be chose between sensor node and sink node when the number of sensor nodes increases. Therefore, the network can provide more longer lifetime. For these constructed topologies in Fig.7, the network lifetime of the topology constructed by UDG is less than that of other algorithms. Moreover, we already set the 5000 hours as a network lifetime upper bound, which means this times can operate perpetually. In Fig.7, the network lifetime of proposed TFTTM algorithm is more than other algorithms and achieves perpetual monitoring when the number of sensor nodes is equal to 80. However, the FGSS and LTRT both need 90 sensor nodes. In Fig.8, assuming the number of sensor nodes is 50 in monitoring network, we compare the network lifetime of the proposed TFTTM algorithm with other algorithms based on 20 to 80 monitoring targets. From Figure 8, the reduction in network lifetime is less than other algorithms. The proposed TFTTM algorithm has a longer network lifetime than the UDG, FGSS and LTRT.

Furthermore, we further evaluate the monitoring performance of the proposed TFTTM algorithm by ns-2 simulation. The parameters are shown in Table 1. The throughput and delay of receive monitoring date at the sink are evaluated. We utilize UDP connection and CBR flow from target nodes to sink node. The packet length of monitoring data is 512bytes and the sending rate of each CBR flow is fixed at 256 kbps. All transmissions are unicast following the 802.11 protocol. Under the condition of the same fault tolerant requirement k=2, we compare the performance by measuring the throughput and average delay. The comparison result is shown in Fig.9 and Fig.10.

Table 1. Simulation parameters

Field size	1000m × 1000m
Maximum transmission range	250m
Monitoring range	200m
Number of sensor nodes	50-100
Number of target nodes	40
MAC protocol	802.11
Traffic pattern	CBR
Trans. protocol	UDP
Packet Length of monitoring target	512 bytes

For evaluation of throughput performance in Fig.9, the proposed TFTTM algorithm achieve higher throughput than other algorithms. Furthermore, the average delay form target nodes to sink node of proposed TFTTM algorithm is lower than other algorithms. These results also validate the correctness of performance comparison in Fig.6. Similarly, the less node degree and path hops for our proposed algorithm respectively have less node interference and transmission delay, which indirectly prove the better performance of the proposed TFTTM algorithm in Fig.10. Since FGSS and LTRT consider the fault tolerant among sensor nodes, it causes the increase of the node degree and path. However, our TFTTM algorithm mainly focuses on the fault tolerant connection between target nodes and sink node, also between sensor nodes and sink node. Thus, from these simulations results, our TFTTM algorithms under the fault tolerant of target monitoring achieve better network performance.

6. **Conclusion.** In this paper, we have investigated the topology optimization problem of fault tolerant target monitoring for energy harvesting WSN and analyzed the relationship between topology optimization and fault tolerant target monitoring. Then, the

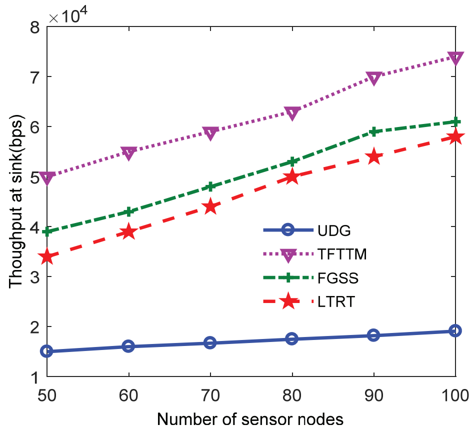


FIGURE 9. Throughput from sink node

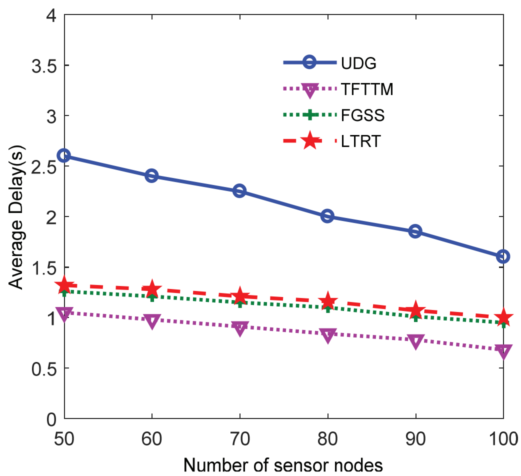


FIGURE 10. Average delay form target nodes to sink node

topology optimization algorithm of fault tolerant target monitoring(TFTTM) is proposed. Extensive simulations show that our proposed algorithm has lower average node degree and shorter average path hops than the existing typical fault tolerant topology control algorithms. In addition, the simulation results of network lifetime, throughput and transmission delay further validate that the proposed TFTTM algorithm improves the network performance for different numbers of sensor nodes and monitoring target nodes.

Acknowledgment. This work is supported by the National Natural Science Foundation of China (Grant No. 61401189), Natural Science Foundation of Jiangxi Province, China (Grant No. 20161BAB212036, 20151BAB207039), The Key Research and Development Program of Jiangxi province (Grant No. 20161BBE50093),the Open Research Fund of Jiangxi Province Key Laboratory of Water Information Cooperative Sensing and Intelligent Processing (Grant No. 2016WICSIP023, 2016WICSIP028, 2016WICSIP030).

REFERENCES

[1] A. K. Yadav, R. S. Yadav, R. Singh, A. K. Singh, An adaptive, energy-aware and distributed fault-tolerant topology-control algorithm for heterogeneous wireless sensor networks, *Ad Hoc Networks*, vol. 44, no. C, pp. 104-117, 2016.

[2] T. -T. Nguyen, J. -S Pan, S. -C Chu, J. F. Roddick, and T. -K Dao, Optimization localization in wireless sensor network based on multi-objective firefly algorithm, *Journal of Network Intelligence*, vol. 1, no. 4, pp. 130-138, 2016.

[3] F. Yakine, A. Idrissi, Energy-aware topology control and Qos routing in Ad-Hoc networks, *Procedia Computer Science*, vol. 56,no.1, pp. 309-316, 2015.

[4] Y. -J Chen, G. -J Horng, and S. -T Cheng, A Distributed Cross-Layer Compromise Detection Mechanism for Wireless Sensor Networks, *Journal of Network Intelligence*, vol. 2, no. 1, pp. 147-161, 2017.

[5] F. K. Shaikha, S. Zeadally, Energy harvesting in wireless sensor networks: a comprehensive review, *Renewable and Sustainable Energy Reviews*, vol. 55, pp.1041-1054, 2016.

[6] A. Cammarano, C. Petrioli, D. Spenza, Online energy harvesting prediction in environmentally powered wireless sensor networks, *IEEE Sensors Journal*, vol. 16, no.17, pp. 6793-6804, 2016.

[7] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, Power management in energy harvesting sensor networks, *ACM Transactions on Embedded Computing Systems*, vol. 6, no. 4, article 32, 2007.

[8] M. Hassan, A. Bermak, Solar Harvested energy prediction algorithm for wireless sensors, *Symposium on Quality Electronic Design*, vol. 48, no. 11, pp. 178-181, 2012.

[9] M. Younis, I. F. Senturk, K. Akkaya, S. Lee, F. Senel, Topology management techniques for tolerating node failures in wireless sensor networks: A survey, *Computer Networks*, vol. 58, no. 1, pp. 254-283, 2014.

[10] D. M. Blough, M. Leoncini, G. Resta, P. Santi, The k-neighbors approach to interference bounded and symmetric topology control in ad hoc networks, *IEEE Trans. on Mobile Computing*, vol. 5, no. 9, pp. 1267-1282, 2006.

[11] X. Wang, M. Sheng, M. Liu, D. Zhai, and Y. Zhang, RESP: A k-connected residual energy-aware topology control algorithm for ad hoc networks, *in Proc. of IEEE Wireless Communications Networking Conference*, pp. 1009-1014, 2013.

[12] L. Li, Y. H. Joseph, B. Paramvir, Y. M. Wang, R. Wattenhofer, A cone-based distributed topology-control algorithm for wireless multi-hop networks, *IEEE Transactions on Networking*, vol. 13, no. 1, pp.147-159, 2005.

[13] N. Li, J. C. Hou, Localized fault-tolerant topology control in wireless ad hoc networks, *IEEE Trans. on Parallel and Distributed Systems*, vol. 7, no. 4, pp. 307-320, 2006.

[14] K. Miyao, H. Nakayama, N. Ansari, LTRT: an efficient and reliable topology control algorithm for Ad-Hoc networks, *IEEE Transactions on Wireless Communications*, vol. 2, no. 8, pp. 6050-6058, 2009.

[15] J. Guo, X. Liu, C. Jiang, J. Cao, Y. Ren, Distributed fault-tolerant topology control in cooperative wireless Ad Hoc networks, *IEEE Transactions on Parallel and Distributed Systems*, vol. 26, no.10, pp.2699-2710, 2015

[16] K. N. Dong, J. Hur, Energy-aware topology control for reliable data delivery in solar-powered WSNs, *Eurasip Journal on Wireless Communications & Networking*, vol. 2013, no. 1, pp.258-271, 2013.

[17] Z. Yin, F. Li, M. Shen, Y. Wang, Fault-tolerant topology for energy-harvesting heterogeneous wireless sensor networks, *2015 IEEE International Conference on Communications, 2015 ICC*, pp. 6761-6766, 2015.

[18] T. Böhme, F. Göring, J. Harant, Menger's theorem, *Journal of Graph Theory*, vol. 38, no.1, pp. 35-36, January, 2001.

[19] C. Yang, K. W. Chin, Novel algorithms for complete targets coverage in energy harvesting wireless sensor networks, *IEEE Communications Letter*, vol. 18, no.1 pp. 118-121, 2014.