A TOPOLOGY CONTROL ALGORITHM TAKING INTO ACCOUNT ENERGY AND QUALITY OF TRANSMISSION FOR SOFTWARE-DEFINED WIRELESS SENSOR NETWORK

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ABSTRACT

The efficient use of energy in wireless sensor networks is critical for extending node lifetime. The network topology is one of the factors that have a significant impact on the energy usage at the nodes and the quality of transmission (QoT) in the network. We propose a topology control algorithm for software-defined wireless sensor networks (SDWSNs) in this paper. Our method is to formulate topology control algorithm as a nonlinear programming (NP) problem with the objective to optimizing two metrics, maximum communication range, and desired degree. This NP problem is solved at the SDWSN controller by employing the genetic algorithm (GA) to determine the best topology. The simulation results show that the proposed algorithm outperforms the Max Power algorithm in terms of average node degree and energy expansion ratio.

KEYWORDS

SDWN, topology control, genetic algorithm, nonlinear programming.

1. INTRODUCTION

Wireless Sensor Networks (WSNs) are increasingly being used in a variety of fields, particularly during this period of rapid growth in internet of things applications. The WSNs can be controlled in three ways: centralized control, decentralized control, and distributed control [1]. The centralized control model includes a node in the network that stores global information. This node controls the data transmission from sensor nodes to the base station (BS). The decentralized control model divides all sensor nodes into clusters, with one node acting as the cluster leader in each. Data is sent from sensor nodes to the BS via the cluster head node. For the distributed control model, the sensor nodes play the same role. Control functions are distributed among the nodes.

To boost the performance of WSNs, some published research has examined architectures, models, as well as control protocols in the network, where topology control algorithms are an interesting topic, attracting many research groups recently [2]-[9], [19]. For this topic, the authors of [6] have proposed an energy efficient topology control algorithm namely RL-CRC (Reinforcement Learning-based Communication Range Control). The RL-CRC algorithm uses

DOI: 10.5121/ijcnc.2024.16207

reinforcement learning to adaptively adjust the communication range of each node in WSN. To do this, the authors have proposed a reward function that includes two metrics, the node degree and the communication range. This reward function is used for nodes to tune its communication range to obtain the optimal topology. According to the simulation results, RL-CRC consumes much less energy than traditional methods while retaining about the same average communication range and node degree. In [7], the authors have proposed a topology control algorithm for ad-hoc networks namely LTRT (Local Tree-based Reliable Topology). It has been demonstrated theoretically that the LTRT algorithm ensures k-edge connection while maintaining the properties of the local minimal spanning tree. The efficiency of LTRT and its superiority over other localized algorithms have been demonstrated by simulation results. In [8], a topology control algorithm named FLSS (Fault-tolerant Local Spanning Sub-graph) has been proposed for wireless ad-hoc networks. The FLSS algorithm minimizes the maximum transmission power used in the network. According to simulation results, FLSS not only has better power efficiency than existing fault-tolerant topology control algorithms, but it also leads to higher network capacity. Topology control using fuzzy logic was also implemented in [9]. In this work, a novel Fuzzy logic-based Topology Control (FTC) algorithm is proposed with the main objective is to improve the network connectivity. The method of the FTC algorithm is to adaptively change communication range in order to achieve any desired average node degree. The performance of algorithm FTC is compared with other well-known algorithms by simulation method.

Recently, the SDN-based centralized control model has been applied to the WSNs [1], [10], [11]. depicts the basic principle of this model. The sensor nodes are either directly or indirectly connected to the SDN controller via the open- flow protocol. Control functions in the network, such as routing, signaling, topology control, and so on, are concentrated at the SDN controller. The SDWSN model has been used to improve control protocols in the WSN network, most notably routing protocols [12], [13], topology control [14], [15], and clustering protocol [16], [17]. For the topic of topology control using SDN, the authors in [15] proposed a

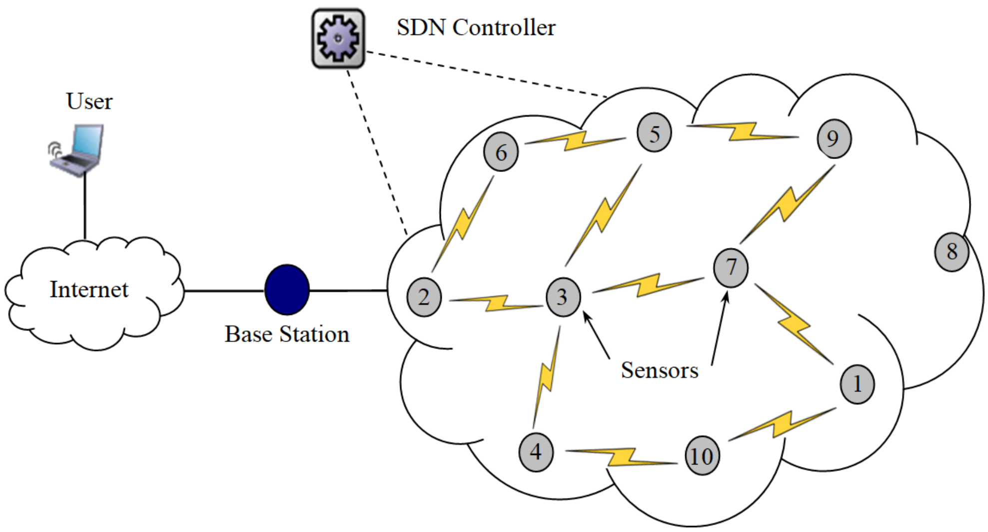


Figure 1. An example of software-defined wireless sensor networks (SDWSN)

decentralized topology control algorithm with the goal of improving the efficiency of energy use. The algorithm is named EEHTC (Energy-Efficient Hierarchical Topology Control) dividing the control into two layers. One is to control the topology in the lower layer with conventional sensor nodes. The second is to control the topology in the upper layer for software control sensor nodes. When comparing with other algorithms, the EEHTC algorithm increases the existence time of nodes and reduces energy consumption. In [18], the authors have proposed a SDN-based manageable topology formation for flying ad hoc networks (FANET) to reduce the mobility negative effects of UAVs on the communication and improve the network performance. Simulation results have shown that the proposed solution gives high efficiency in terms of packet loss within the required delay limit.

We discovered from the published research projects that topology control is a successful method for enhancing network performance, particularly in terms of enhancing energy efficiency. There are many various ways to implement topology control algorithms, however adopting SDWSN as one of them provides numerous benefits. This is due to the algorithm being run at the SDN controller in accordance with the centralized control principle, which makes it easy to optimize performance metrics. In this paper, we suggest a new topology control algorithm for SDWSNs. Using a nonlinear programming (NP) problem, we develop the topology control algorithm with the objective of optimizing the maximal communication range and desired degree. At the SDWSN controller, this NP problem is resolved by using the genetic algorithm (GA) to select the optimal topology.

The next sections of this paper are organized as follows. Section 3 presents our proposed routing algorithm. Some simulation results and discussion are presented in section 3. Finally, concluding remarks and promising future study items are given in Section 4.

2. OUR PROPOSED ALGORITHM

2.1. Concepts and Metrics

In this section, we express the concepts and metrics that will be used for the objective function and the constraints in our proposed algorithm in the next sub-section.

2.1.1. Connected Node

A sensor node I is referred to as the connected node if and only if there is at least one route from it to BS. Returning to the example as shown in node 8 is not a connected node because there is no route from it to BS. The connected node is represented by all the remaining nodes.

2.1.2. Desired- Proximity Degree Node

A Desired-proximity degree node is defined as a node whose degree is within the range [k-γ, k+γ], where k is the desired degree and γ is a given positive integer. Let λ_i be a variable indicating whether node I is a k-proximity degree node or not, return 1 if it is true and 0 otherwise. Then λ_i is determined by

$$\lambda_i = \begin{cases} 1 & if\ \ k-\gamma \le \delta_i \le k+\gamma \\ 0 & otherwise \end{cases} \tag{1}$$

where δ_i is the degree of the node I, defined as the number of its neighbours.

2.2. Our Proposed Algorithm

In this section, we present the SDN-based QoT and Energy efficient Topology Control (SQETC) algorithm, proposed for SDWSNs. The main goal of the SQETC algorithm is to create a topology that maximizes energy efficiency at nodes while also providing the best QoT in the network. In an SDWSN topology, the degree of the nodes has the greatest influence on the energy consumption. We, therefore, use the metric λ_i as defined in **(1)** to optimize energy use. In addition, the communication range of each node is used to optimize the QoT in the network. Thence we define a fitness function as follows:

$$F = \alpha \frac{n - \sum_{i=1}^{n} \lambda_i}{n} + (1-\alpha)\frac{Max_{i=1..n}(r_i)}{r_{\max}} \quad (2)$$

where α is a floating parameter in the range [0, 1] which is used to control the importance of metrics. The SQETC algorithm can be formulated as a nonlinear programming (NP) problem as follows:

$$Minimize\ (F) \quad (3)$$

subject to the following constraints:

$$r_{\min} \le r_i \le r_{\max}, \forall i \in N \quad (4)$$

$$c_i = 1, \forall i \in N \quad (5)$$

where r_{min} and r_{max} are the minimum and maximum communication range of each node, respectively. Equations **(4)** is the constraints of the communication range of sensor nodes. Equations **(5)** is the constraints of network connectivity, where c_i is a variable indicating whether the node *I* is the connected node or not, determined by.

$$c_i = \begin{cases} 1 & if\ I\ is\ a\ connected\ node \\ 0 & otherwise \end{cases} \quad (6)$$

By solving the NP problem with the objective function **(3)**, the constraints **(4)** and **(5)**, we find the solution $R = \{r_i | i = 1 .. N\}$ which is the optimal communication range of nodes so that the resulting topology has the mean degree of nodes close to the desired degree.

Algorithm 1. The pseudo code of the SQETC algorithm	
(1)	The SDN controller collects information about the location and communication range of each node through control packets;
(2)	Formulate the NP problem according to **(3)**, (4), and (5);
(3)	Solve the NP problem in step (2);
(4)	**for** (*each node i* ∈ *N*)
(5)	Adjust the communication range of the node *i* based on the solution
(6)	found in step (3);
(7)	**endfor**;
(8)	Create the topology based on adjusted communication ranges of all nodes;

Algorithm 1 presents the pseudo-code of the SQETC algorithm. Each node sends a control packet to the SDN controller containing information about its current location and communication range whenever the topology network needs to be updated. Based on this information, the SDN controller formulates the NP problem according to (3), (4) ,and (5). This NP problem is solved at the SDN Controller by an approximate optimization algorithm. In this work, we use a genetic algorithm (GA) to solve it, which returns the communication range of each node. Based on this result, the node adjusts its communication range to obtain the optimal topology.

3. PERFORMANCE EVALUATION

3.1. Simulation Scenarios

The performance of the SQETC algorithm was evaluated by simulation method using Matlab software. We use the GA algorithm in the Matlab optimization tool to solve the NP problem that is proposed in subsection 2.2. The SQETC algorithm is compared with the network topology case using maximum power, named MaxPower. The MaxPower is the default case in wireless networks in general, and WSN in particular. In this case, the nodes always operate with the widest possible communication area. A wireless connection is formed when two nodes are within range of each other. The network topology is comprised of all nodes and wireless connections. Evaluation metrics include average node degree, energy consumption rate, and path loss. Tables 1 and 2 show how the simulation scenarios are configured. Despite the randomness of the GA optimization algorithm, each scenario is run 50 times to ensure the objectivity of the simulation results. The findings presented in this paper are based on an average of 50 simulations.

Table 1. Technical parameters of simulation scenarios

Parameters	Setting
Network area	1000 × 1000 [m^2]
Maximum communication range	250 [m]
Number of sensor nodes	From 40 to 100
Desired degree of each node (k)	From 3 to 5
Coefficient γ	1
Topology control algorithm	SQETC, MaxPower
Optimal algorithm for solving NP problem	GA
Number of simulation runs per scenario	50

Table 2. GA algorithm parameters used to solve the NP problem of the SQETC algorithm

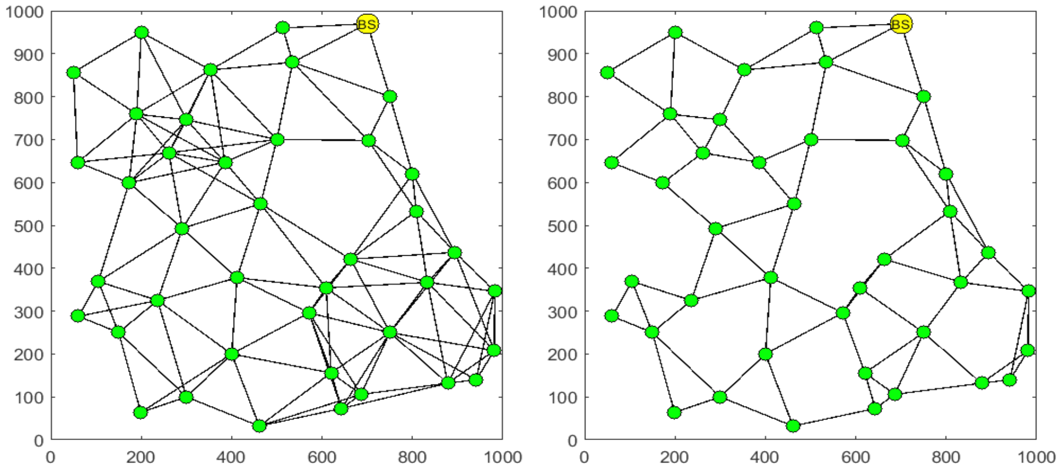
Parameters	Setting
Selection function	Stochastic uniform
Crossover function	Scattered
Mutation function	Adaptive feasible
Population size	50
Max iteration	1000

3.2. Simulation Results

Figure **1** compares the network topology obtained using SQETC and MaxPower algorithms. In this case, the number of sensor nodes is 40 and the desired degree of each node is 4. We can observe that, in the case of MaxPower (result in

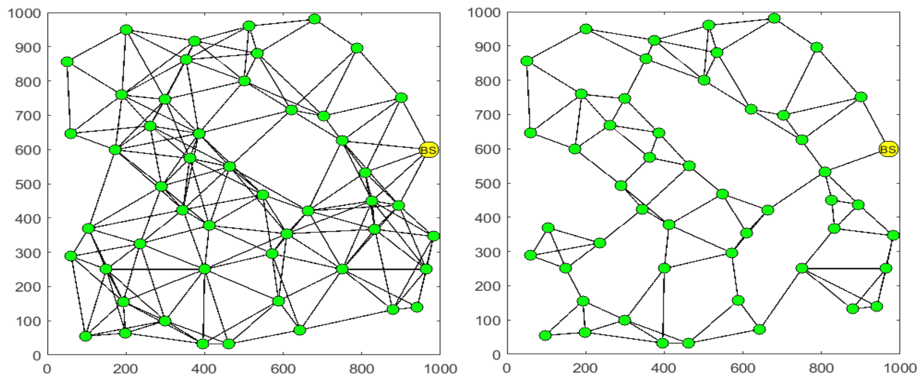
Figure **1**a), the topology consists of many wireless links between nodes. The maximum, minimum and mean of node degrees are 11, 3 and 6, respectively. This topology is inefficient because the degree difference between the nodes is quite large, easily leading to bottleneck congestion at some nodes when data transmission. In addition, because the topology has many wireless links, the nodes have to spend a lot of energy to maintain the links. For the case of using SQETC algorithm (results in

Figure **1**b), the obtained topology has a balanced degree of nodes. The maximum, minimum and mean of node degrees are 5, 2 and 3.67, respectively. Thus, the average node degree is very close to the desired degree (k = 4), this topology is more optimal than the topology of the MaxPower algorithm.



(a) (b)

Figure 1. SDWSN topology comparison when using algorithms (a) MaxPower and (b) SQETC in case the number of nodes is 40, desired degree is 4.



(a) (b)

Figure 2. SDWSN topology comparison when using algorithms (a) MaxPower and (b) SQETC in case the number of nodes is 50, desired degree is 4.

The obtained results are also quite similar for the simulation scenario where the number of sensor nodes is 50, this is clearly shown in Figure 3. In the case of MaxPower (result in Figure 3a), The maximum, minium and mean of node degrees are 12, 3 and 7.36, respectively. Thus, the node degree difference is also very large. In case the SQETC algorithm is used, the resulting topology has a more balanced node degree and is closer to the desired degree. Specifically, the mean degree is 3.85. These results have shown that the topology obtained using the SQETC algorithm is more optimal than in the case of MaxPower.

Next, we examine the average node degree versus the number of nodes. The results are shown in Figure 4 and Figure 5 for the cases where the desired degree is 4 and 5, respectively. We can observe that, in the default case (MaxPower), the larger the number of nodes, the higher the average node degree. This is obvious because when the number of nodes is large, the node density is thicker. Because the MaxPower algorithm configures the topology using the maximum communication range, each node will have many neighbors. For the SQETC algorithm, the average node degree is close to the desired degree even when the number of nodes is large. Specifically, considering the case of the desired degree of 4, the topology obtained by the SQETC algorithm has an average degree of 3.71 (Figure 4). In the case of a desired degree of 5, the average node degree of the topology is 4.82 if the SETC algorithm is used.

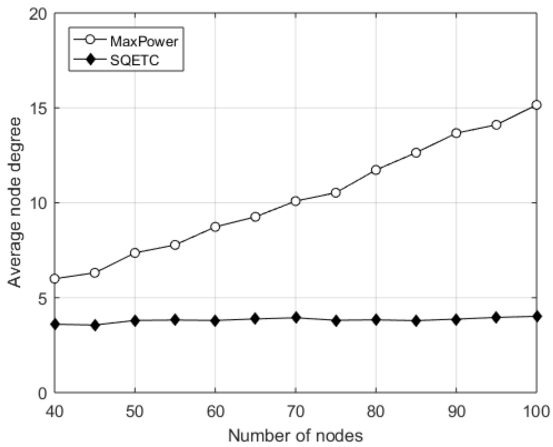


Figure 3. Compare average node degree of algorithms SQETC and MaxPower when desired degree is 4

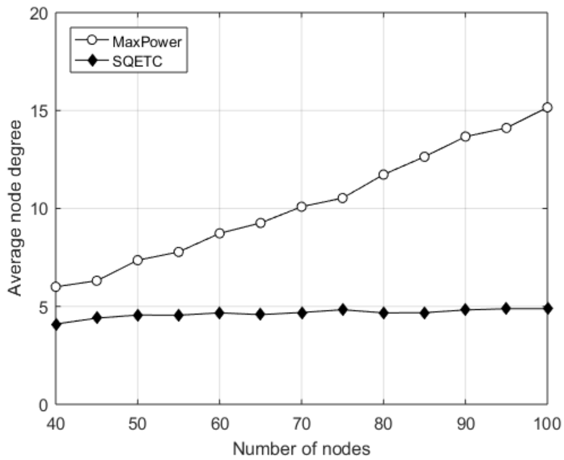


Figure 4. Compare the average node degree of algorithms SQETC and MaxPower when the desired degree is 5

Since the topology obtained by the SQETC algorithm has an average degree closer to the desired degree than in the case of MaxPower, the SQETC algorithm provides better energy efficiency. This is evident in the results obtained in Figures 6 and 7. Energy efficiency is analyzed through the metric of energy expansion ratio (EER), which is determined by [7]:

$$EER = \frac{E_{ave}}{E_{\max}} \times 100\,[\%] \qquad \textbf{(7)}$$

where E_{ave} is the average transmission power of all nodes and E_{max} is the maximum transmission power to reach the maximum communication range (250 [m] in simulation scenarios).

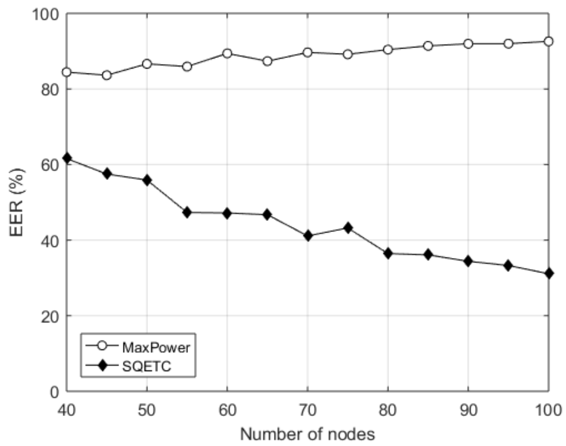


Figure 5. Compare energy expended ratio of algorithms SQETC and MaxPower when desired degree is 4

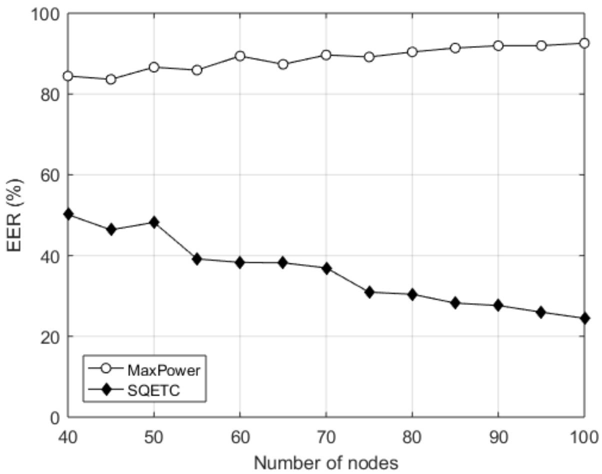


Figure 6. Compare energy expended ratio of algorithms SQETC and MaxPower when desired degree is 5

The results obtained in Figure 6 and Figure 7 show that, the EER in the case of using the SQETC algorithm is much lower than that of the MaxPower algorithm. Considering the case of total nodes is 50, the EER for the case of MaxPower is 86.64%. Meanwhile, if using the SQETC algorithm, the EER is only 48.22% and 55.90% respectively for the cases where the desired node degree is 4 and 5. For the cases where the number of nodes is larger, the EER is lower when the number of nodes is higher. Thus, the SQETC algorithm brings high energy efficiency, especially with WSNs where the nodes are highly distributed.

4. CONCLUSIONS

Topology control in SDWSN is a research topic that has attracted the attention of many research groups recently. An optimized network topology improves network performance. In this paper, we propose a new topology control algorithm for SDWSNs. Our approach is to model topology control as an NP problem with the goal to optimizing two metrics: maximum communication range and desired degree. This NP problem is solved at the SDWSN controller by employing the GA algorithm. In terms of average node degree and energy efficiency, the simulation results show that the proposed algorithm outperforms the MaxPower case.

Although our proposed algorithm improved SDWSN performance, in the case of rapidly moving nodes, the network topology must be updated regularly. As a result, the computational complexity at the SDN controller grows. This is a limitation of the proposed algorithm. We will continue to research solutions to this problem in the future.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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