Network Topology Algorithm Based on Energy-consumption Optimization of Multi-hop Wireless Networks

Wu Weiwei  
Department of Basic Courses, Jiangsu College of Engineering and Technology, Nantong, Jiangsu, 226000, China  
Email: www@jcet.edu.cn

Sun Hua  
School of Information Engineering, Yancheng Institute of Technology, Yancheng, Jiangsu, 224000, China

Abstract—A balanced topology intervention algorithm based on energy-consumption optimization is presented in this paper. Multilayer sequence planning algorithm is firstly adopted to convert the nonlinear optimization problem into edge-stirring mechanism and node-stirring mechanism so as to independently optimize these sub-problems, and then the solutions of these problems are adopted to analyze the potential balanced performance between energy consumption and average path-length in the networks. Through simulation under different network scale and operational requirement, the validity and applicability of the algorithm are verified. In addition, we have found the balance point between edge-stirring mechanism and node-stirring mechanism in the network with energy and throughput constraints.

Index Terms—Wireless Multi-Hop Networks; Topology Intervention; Network Stirring; Future Internet; Energy-Consumption Optimization

I. INTRODUCTION

Wireless sensor networks can provide a low-cost, effective, and reliable solution for health monitoring, scientific data collection, environmental monitoring and military operations. Wireless multi-hop network (WMHN) [1] is an important characteristic of the future Internet. Generally speaking, wireless multi-hop network consists of a small, energy-constrained and affordable wireless device [2] [3]. The size and scale of wireless multi-hop network are multiple so as to adapt some different applications scenarios [4]. One drawback of wireless multi-hop network diversity is the lack of the effective coordination of central base-station, which results in the changing networks properties. In wireless multi-hop network, the communication distance (average hop-length) between the communication node-pairs is often very long, which restricts the end-to-end performance [5] [6] [7]. In order to solve the performance of multi-hop wireless networks [8], researchers have proposed a stochastic geometry graph theory. In order to perfect wireless multi-hop network in the future, some properties in a small-scale network [9] [10] (smaller average path length) have been applied to multi-hop network, which has abstracted considerable attention in the recent years.

Wireless shortcut algorithm is an improved algorithm based on wireless multi-hop network topology. If a node can make the number of average-hops reduce, the node is called wireless shortcut. The wireless shortcut algorithm has been adopted to enhance network topology performance of sensor networks or Ad Hoc networks in the existing researches, but different criteria determines the different wireless shortcut or wireless shortcut algorithm. The improved methods are the inverse topology control (iTC) [11] [12] [13] and the network stirring, which are more general algorithms for adjusting the overall network topology. The wireless shortcut can be produced via increasing the wireless coverage of the selected node, [14] and if necessary, the reversible process can be adopted to adjust the topology. The topology process also considers the removal process for links and nodes so as to balance the number of links and nodes [15] [16]. Typically, different node-stirring (node addition and deletion) and edge-stirring (link addition and deletion) can obtain a dynamic intervention mechanism for wireless multi-hop network topology [17] [18]. However, the node energy has a polynomial relationship with its transmission radius, which will eventually be reflected in the inherent compromise performance between average path-length and network energy-consumption [19] [20]. In this aspect, some researchers have attempted to optimize the allocation of long-distance network topology links, where the optimization objective includes energy-consumption minimization and load-balancing [21]. For example, some scholars have tried to use simulation average path-length to reduce the wireless shortcut and the minimum hop length as much as possible [22]. Genetic optimization algorithm is also used to maximize the path length and minimize the configure wireless shortcut. Inverse topology control algorithm assumes that the wireless shortcut with power control mechanism is more suitable for the distributed configuration and dynamic reconfiguration in wireless shortcuts [23]. In addition, it
also can be adapted to the requirement of individual nodes, and then ultimately meet the requirement of the entire network [24]. Therefore, the configuration of wireless shortcut is optimized so as to reduce costs function, namely, extra energy-consumption, which is very suitable for wireless multi-hop networks [25].

An optimization algorithm is introduced to analyze the trade-off performance of path-length and energy-consumption. The algorithm uses the stirring mechanism induced by power so as to ensure the wireless shortcuts [26] [27]. The given optimal control mechanism can ensure an ideal network average path length and a minimum energy-consumption. This approach has produced another compromise, which is edge-stirring mechanism and node-stirring mechanism. The edge-stirring mechanism can reduce more path-length, while the node-stirring mechanism makes energy efficiency much higher. Thus, this compromise can be controlled in accordance with the network demand so as to ensure the instantaneous ideal equilibrium between path length and energy efficiency.

The rest of this paper is organized as follows. The detailed analysis of topology intervention mechanism is provided in Section one, including network model, stirring pattern, and the inverse topology control. The edge-stirring mechanism is adopted to solve network hierarchical structure in Section two. And then the theoretical compromise model is introduced and analyzed in Section three. The fourth Section will analyze and derive the path-length, threshold and the maximum energy-efficiency. The experimental results are shown and analyzed in Section five, and the conclusion is made in Section six.

II. TOPOLOGY INTERVENTION MECHANISM

This section introduces the topology intervention mechanism based on iTC algorithm and network-stirring. This mechanism has introduced some characteristics of the small-scale network into wireless multi-hop network. Network stirring mechanism includes two mechanisms: edge-stirring mechanism and node-stirring mechanism.

![Topology intervention mechanism model](image)

Topology intervention mechanism is shown in Figure 1, which is performed in the network topology. The network is a square region with \(L\) length, the initial transmission radius is \(R_i\) where there are \(N\) nodes and these nodes are randomly and uniformly distributed within the transmission area. In addition, each node can change its transmission radius, where the range is \([R_i, R_{MAX}]\).

Time is divided into time-slots, and each time-slot is denoted by two radius parameter. These two radius parameters are \(R_{\text{min}}(t)\) and \(R_{\text{max}}(t)\) where \(R_i \leq R_{\text{min}}(t) \leq R_{\text{max}}(t) \leq R_{\text{MAX}}\). Initially, we have \(R_i = R_{\text{min}}(0) = R_{\text{max}}(0)\), and then \(R_{\text{max}}(t) = R_i + at\), which shows that the value of \(R_{\text{max}}(t)\) increases a predefined value \(a\), while \(R_{\text{min}}(t)\) is an lower bound of \(R_{\text{max}}(t)\) [28] [29]. The maximum number of steps is \(R_{\text{MAX}} - R_i\), where it is subjected to the maximum power \(a\) of node and \(R_i(t), R_i \leq R_{\text{min}}(t) \leq R_{\text{max}}(t)\) is the instantaneous transmission radius of node \(i\).

Network stirring involves changes of links and nodes (node’s addition, deletion and reconnection, edge’s addition and deletion). Network stirring mechanism consists of two basic sub-mechanisms, namely, edge-stirring mechanism and node-stirring mechanism. Edge-stirring mechanism refers to edge addition and deletion which can be realized by the protocol stack in the physical and network layers. According to the results of the existing literature 8, the occurrence probability of edge-addition is \(p\), and \(m_t\) directed-links are increased for \(m_t\) nodes so as to add 1 to the out-degree of each node. In the process of link-added, \(m_t\) suitable node are firstly selected and the coverage area \(R_i(t)\) of each node will be extended to \(R_{\text{max}}(t)\), which has formed a large range of connection for network layer. In other words, only node \(j\) is selected as center, where the radius of the inner ring is \(R_{\text{min}}(t)\) and outer radius is \(R_{\text{max}}(t)\), and the ring is denoted as \(A_{\text{new}}^{\text{min}}(i)\). To ensure that there is at least one node in each ring, appropriate parameters \(a\) are selected according to the network density. The probability of edge deletion is \(\tau\), and \(m_t\) links are deleted. In the process of the deletion, each selected node \(i\) will remove a network layer connection \(i \rightarrow j\), where the node \(j\) is an one-hop neighborhood of node \(i\).

Similarly, the node stirring includes nodes addition and deletion. The occurrence probability of the node addition is \(w\) and increases new nodes with radius \(R_{\text{max}}(t)\) by \(M_u\). As for each addition node, if the connected node is located to the circular area \(\pi R_i^2\), the connection is bidirectional. When the connection node is in the ring \(E(i, \bar{P}) = \sum_{v 
} cR_i(i, \bar{P})\), the connection is directed. The probability of node deletion is \(v\). And select \(M_u\)
nodes to delete. Obviously, the node stirring changes the number of node in networks, \( p \{ r, v, w \} \) vector constitutes a probability distribution, and only one type of intervention has occurred at each moment.

III. OPTIMIZING CONTROL ALGORITHM

As mentioned above, one can add some characteristics of small-scale network into random geometric diagram by controlling (expanding) the wireless coverage of the selected nodes. However, for each transmission, the node energy-consumption after intervention has a polynomial increase according to its transmission range. This paper aims at providing an optimization method to get the optimal parameter of topology intervention in inverse topology control network, so that the inverse topology control network can meet some optimization demands, for example, ideal average path-length and lower extra overhead. Therefore, in inverse topology control system, the paper attempts to optimize parameter vector \( \bar{P} = \{ p \ R_t \ P \ \} \) so as to achieve a good compromise of specific demands and energy-consumption. According to the instantaneous operation and network design requirement, the vector \( \bar{P} \) can also form a control system, which balances the compromise of the corresponding requirement and the energy-consumption.

Then, a constraint optimization problem related to vector \( \bar{P} \) is proposed to solve the problem of compromise. Therefore, the optimization object has connection with the energy-consumption of network coding. A given transmission radius is directly proportional to the node transmission power so as to precisely describe node energy-consumption in the consideration of the same transmission time of all information. Then the network energy-consumption can be denoted as \( E(t, \bar{P}) = \sum_{i=1}^{N(t, \bar{P})} cR'(t, \bar{P}) \), where \( y \) is the path-loss constant related to communication medium \( y \in [2, 4] \); \( c \) is constant; \( N(t, \bar{P}) \) is the nodal point; \( R'_i(t, \bar{P}) \) is the radius of node \( i \) when time is \( t \) and parameter vector is \( \bar{P} \). However, because the analytic expression of \( R'_i(t, \bar{P}) \) in multi-hop network is very complicated and has a close relationship with energy, it is difficult to obtain the analytic expression of wireless multi-hop network. Nevertheless, average radius \( \bar{P}_{avg} \) is suitable for the relation \( \sum_{i=1}^{N(t, \bar{P})} R'_i(t, \bar{P}) = N(t, \bar{P}) \bar{R}_{avg}(t, \bar{P}) \) in each time-step, so \( \left( \sum_{i=1}^{N(t, \bar{P})} R'_i(t, \bar{P}) \right) = \left( N(t, \bar{P}) \bar{R}_{avg}(t, \bar{P}) \right) \), which means \( \sum_{i=1}^{N(t, \bar{P})} R'_i(t, \bar{P}) \leq N(t, \bar{P}) \bar{R}_{avg}(t, \bar{P}) \). The given maximum time step is denoted as \( T \) (defined as the possible maximum transmission power of network node), which can minimize \( N(T, \bar{P}) \bar{R}_{avg}(T, \bar{P}) \) and then minimize the upper bound of \( E(t, \bar{P}) \). Based on the probability model of iTC topology intervention system, it is possible to obtain the analytic expression of the upper bound of \( N(T, \bar{P}) \bar{R}_{avg}(T, \bar{P}) \).

A. The Upper Bound of Average Transmission Radius

The constraint set of optimization problems should express the small-scale characteristics of the final topology. As for a simple random topology, the analytic expression of average path-length is still difficult to be obtained in a wireless multi-hop network. In addition, there is a close relationship between average path-length and wireless shortcut. The length of average path decreases as the number of long links increases. Therefore, the study about average transmission power is not limited in the average path length, but can be extended to analyze the wireless shortcut number \( L(T, \bar{P}) \) of network topology.

Based on the topology intervention system mentioned above, the analytic expression of upper bound can be shown. In each time-slot, the average number of nodes \( \sum_{i=1}^{N(t, \bar{P})} R'_i(t, \bar{P}) = N + wM_{ij} - vM_{ij} \) is known, so the expression of \( \bar{R}_{avg}(T, \bar{P}) \) is as follows:

\[
\bar{R}_{avg}(T, \bar{P}) = \sum_{i=1}^{N(t, \bar{P})} R'_i(t, \bar{P}) = \frac{NR_i + dR_i(t, \bar{P})}{N(t, \bar{P})} (1)
\]

where \( NR_i \) is the sum of the initial nodes radius, \( dR_i(t, \bar{P}) \) is the total variations of all nodes’ radius at the time-step \( t \). Then we will study the influences of iTC sub-system on \( dR_i(t, \bar{P}) \). The deletion of links has no influence because node coverage doesn’t change. At each time-step \( t \), the influence of node can be measured by \( M_{ij}w(R_i + ak) \), because the probability of the added \( M_{ij} \) nodes in network is \( w \) and the node radius is \( R_i + ak \). Considering the influence from node deletion, the utmost affection is \( -M_{ij}vR_i \) (the upper bound of \( dR_i(t, \bar{P}) \)) when the initial radius of all nodes is \( R_i \). The increase of edges has more complicated influences on network, because it may make the node coverage scope strange, and its radius difference \( R_{max}(t) - R_i(t, \bar{P}) \) depends on \( R_i(t, \bar{P}) \). In order to add edge into the definition of \( dR_i(t, \bar{P}) \) upper bound, all links should be added to the nodes with radius of \( R_i(t, \bar{P}) = R_j \). Then the addition of \( dR_i(t, \bar{P}) \) at time step \( k \) can be denoted as \( pm_{ij}ak \), and then the addition of \( dR_i(t, \bar{P}) \) is \( pm_{ij}a \sum_{i=1}^{k} k \).

The upper bound \( \bar{R}_{avg} \) of the probability model is illustrated in equation (2), as shown in Fig. 2 (a, b)
The number of links \( L(t, \bar{P}) \) can be replaced by upper bound \( R_{av}^w(t, \bar{P}) \) in object functions. In addition, it can count the average number of the links. Fig. 2 (b) has illustrated the experiment values and theoretical values of new links in all simulations. These results are also the average numbers of 100 different initial topologies.

If there are \( N \) nodes with random uniform distribution in area \( A \), then the average number of node in area \( B \subseteq A \) is \( \frac{NB}{A} \). So the number of links at time-step \( t \) can be denoted as follows:

\[
L(t, \bar{P}) = \frac{NR_p + M_w R + (M_w + pm_t) a (t' + 1)}{N + wM_t - vM_t} \left( R_c + v \right) \sum_{k=1}^{v} \frac{\pi R^2}{L_k - \bar{P}_k} N(k) - vM_t - wM_t - vM_t - \sum_{k=1}^{v} \frac{\pi R^2}{L_k} N(k - 1)
\]

where the sum terms \( pm_t \) and \( -m_t \) on the right side of the equation are corresponded to edge-stirring mechanism, the sum term \( -2M_v \sum_{k=1}^{v} \frac{\pi R^2}{L_k} N(k - 1) \) are corresponded to node-stirring mechanism. Coefficient 2 expresses that the newly added links are bidirectional links. The above formula can be often abbreviated to

\[
L(t, \bar{P}) = A_1(\bar{P})t^4 + A_1(\bar{P})t^3 + A_1(\bar{P})t^2 + A_1(\bar{P})t \quad (4)
\]

where \( A_1, A_2, A_3, A_4 \) are the functions of vector \( \bar{P} \).

### IV. Simulation Results and Corresponding Analysis

#### A. Compromise of Network-Stirring Mechanism

Optimization is typically non-linear and the optimization toolbox of MATLAB can be adopted to solve this problem. The adopted function is \textit{fmincon}, which can realize the Multilayer sequence planning algorithm. Therefore, a branch-and-bound algorithm is used to obtain the integer solutions for discrete parameters \( m_2, m_3, M_2, M_3 \).

We firstly consider the conditions when \( R_{max} = 350m \) and \( R_{max} = 450m \), where their lower-bound vectors are respectively

\[
LB_1 = \begin{bmatrix} 0.01 & 1 & 0.01 & 1 & 0.01 & 1 & 0.01 & 1 \\
\end{bmatrix} \quad \text{and} \quad LB_2 = \begin{bmatrix} 0.4 & 10 & 0.01 & 1 & 0.01 & 1 & 0.01 & 1 \\
\end{bmatrix} .
\]

In addition, they both have upper-bound \( UB = [1\ N\ 1\ N\ 1\ 20\ 1\ 20] \) in the two cases, where \( N = 750 \), \( n_k = 770 \), \( \ell_0 = 100 - 3000 \), \( R_1 = 150m \) and \( a = 10m \). Therefore, \( R_{max} = 350m \) corresponds to \( T = 20 \), while \( R_{max} = 450m \) corresponds to \( T = 30 \).

Figure 3(a) and 3(b) have respectively shown average path-length to clustering coefficient. These two parameters are obtained by probability topology intervention mechanism described in the first section. There are approximately 9000 directly-links and 20 initial-topologies in initial network. Each topology uses the optimal \( \bar{P} \) which is solved by the proposed optimization algorithm in this paper, so the average path-length and the clustering coefficient are obtained. Then the average value in 20 initial-topologies is taken as eventual average path-length and clustering coefficient.
The minimum performance of $N(T, P)R_{\text{avg}}(T, P)$ is obtained by the proposed algorithm (the normalization of energy function), as shown in Figure 4. From the figure, the minimum radius is growing not only with the increase of $R_{\text{MAX}}$, but also with the increase of the proportion of the edge-stirring process in topology intervention mechanism. Furthermore, we can see from the figure that the influence of edge-stirring parameter on the optimization function value is greater than the influence of the maximum radius $R_{\text{MAX}}$. The optimization functions are approximately equal when $R_{\text{MAX}}$ are 350m and 450m. However, we can see from Fig 3 (a) that the average path length increases not only with the decrease of $R_{\text{MAX}}$ (more and longer wireless Links), but also with the decrease of the proportion of the edge-stirring process in topology intervention mechanism. Performance of clustering coefficient is shown in 3 (b), it can be seen from the figure that the more restricted the edge-stirring process is, the higher the network clustering coefficient is.

The differences suggest that although sub-optimal parameter can improve the performance of path length (the optimal value is down 12%), the radius-sum value increases very much (about 70% relative to the optimal value), which leads to the energy-consumption has also grown considerably in each transmission. Therefore, we must carefully consider whether it is necessary to sacrifice the performance of energy efficiency under the optimal parameters for achieving minimum multi-hop distance.

As mentioned, the edge-stirring mechanism can lead to higher radius-sum value relative to the optimal value,
which makes the least upper bound of energy-consumption much higher. This viewpoint can be verified in Figure 6.

From the statistics in Figure 6, comparing with NC mechanism, EC mechanism makes the increase of radius-sum value more obviously when the number of links is equal so that the least upper bound of energy consumption is much higher. In addition, the node-stirring mechanism can obtain a stable minimum sum-value, which depends on the network link and the maximum radius. Therefore, from the object function value under the node-stirring mechanism, it can be found that our proposed algorithm can obtain the same minimum sum-values for the number of links and the maximum radius $R_{\text{MAX}}$ in different networks. As for node-stirring mechanism, the optimal $R_{\text{MAX}}$ and the number of links can be determined by other parameters, such as the ideal average path-length or clustering coefficient. Different from node-stirring mechanism, the edge-stirring mechanism makes the minimum sum-value of object function increase with the number of links in the network, and the minimum sum-value of the object function also increase with $R_{\text{MAX}}$. It is noticeable that the radius sum-value does not represent the actual normalized energy-consumption of the node (if all nodes are sending data). However, since the energy consumption of the node depends on its transmission power (radius), the radius sum-value is an upper bound of node energy-consumption. Moreover, as for the end-to-end transmission, the energy consumption is dependent not only on the radius of the node on the path, but also on the number of hops on the path, i.e., the number of relay retransmission and the number of collision retransmission on the MAC layer.

In order to clarify the compromise of the path length and the energy-consumption, this simulation experiment focuses on comparing the relationship between average path length and the number of links with the different $R_{\text{MAX}}$ when using the edge-stirring mechanism and node-stirring mechanism with the optimal parameters, as shown in Figure 7.

From the figure, the edge-stirring mechanism can obtain the smaller average hope by comparing with the node-stirring mechanism. Although the edge-stirring mechanism has higher radius-sum value, the proportion of edge-stirring mechanism in network stirring mechanism needs increasing under a variety of restrictive conditions. In order to improve network performance, the adaptive alert parameters are applied to optimize the network, and edge-stirring mechanism is used to overcome the network defect. The algorithm can measure the strength of connections of every pair of nodes. The directed-link has great influences on the operation of the path-length, and the choice of the interaction length is very important. In order to achieve ideal path length, proper proportion of edge-stirring mechanism is required in topology intervention mechanism. As for node-stirring mechanism, numerous nodes are required to reach the same path-length as edge-stirring mechanism.

V. CONCLUSION

According to the network topology intervention mechanism, a balanced topology intervention algorithm based on energy-consumption optimization is presented in this paper, which is based on network stirring. Multilayer sequence planning algorithm is firstly adopted to convert the nonlinear optimization problem into edge-stirring mechanism and node-stirring mechanism so as to independently optimize these sub-problems, and then the solution of these problems are adopted to analyze the potential balanced performance of energy consumption and average path length in the networks. Through simulation under different network scale and operational requirement, the validity and applicability of the algorithm is verified. In addition, even though the failure of some nodes being considered, the algorithm still works effectively in the simulation.

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