Proceedings of the 29th Chinese Control Conference
July 29-31, 2010, Beijing, China

Small Worlds in the Tree Topologies of Wireless Sensor Networks

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Abstract: In this study, the characteristics of small worlds are investigated in the context of the tree topologies of wireless sensor networks. Tree topologies, which construct spatial graphs with larger characteristic path lengths than random graphs and small clustering coefficients, are ubiquitous in wireless sensor networks. Suffering from the link rewiring or the link addition, the characteristic path length of the tree topology reduces rapidly and the clustering coefficient increases greatly. The variety of characteristic path length influences the time synchronization characteristics of wireless sensor networks greatly. With the increase of the link rewiring or the link addition probability, the time synchronization error decreases drastically. Two novel protocols named LEACH-SW and TREEPSI-SW are proposed to improve the performances of the sensor networks, in which the small world characteristics are taken into use to reduce the time synchronization errors.

Key Words: Tree Topologies, Small World, Time Synchronization, LEACH-SW, TREEPSI-SW.

1 INTRODUCTION

The wireless sensor network (WSN) is a class of wireless networks in which sensor nodes collect, process and transmit data acquired from the physical environment to an external base station. These sensor nodes are usually deployed densely in all kinds of sensing fields, and recently more and more efficient ways of the deployment for sensor nodes rise into view. The tree topology is a kind of frequently used architecture, which is ubiquitous in the deployment of wireless sensor nodes. Some network protocols are helpful to construct various tree topologies.

LEACH (Low-energy Adaptive Clustering Hierarchy) [1,2] is a common network protocol, which constructs a two-hop tree topology after the sensor nodes are distributed in the sensing field. If the base station takes the role of the root node in the tree, the cluster-head nodes can be looked upon as the children nodes of the base station and the member nodes as the children nodes of the cluster-head nodes. This tree is constructed in accordance with a certain procedure in the cluster formation phase of LEACH. Each node decides by itself whether to become a cluster-head for the current round with a certain probability. After the cluster-heads are selected, they broadcast their status to other nodes near them in the network. Each sensor node chooses the nearest one as its cluster-head. The two-hop tree topology is constructed after all the nodes find their own roles in the network.

TREEPSI (Tree Based Energy Efficient Protocol for Sensor Information) [3] is another common tree protocol for wireless sensor networks. Different from LEACH, one node is selected randomly as the root node after sensor nodes are deployed in the sensing field. A tree-like hierarchical structure is constructed in accordance with a definite distance threshold on which the node selects its children nodes. The base station computes the tree structure and broadcasts the result to all the nodes. The same tree structure can also be constructed locally by using a common distributed algorithm implemented in each node.

Many novel tree topology protocols have attracted much attention recently. BCDCP (Base-Station Controlled Dynamic Clustering Protocol) [4] introduces a Minimal Spanning Tree (MST) [5] to connect cluster-heads and adopts iterative cluster splitting algorithm to choose cluster-heads or form clusters. DMSTRP (Dynamic Minimal Spanning Tree Routing Protocol) [6] improves BCDCP by introducing MSTs instead of clubs to connect nodes in clusters. TCDGP (Tree-Clustered Data Gathering Protocol) [7] improves the LEACH and TREEPSI, preserving their advantages and improving the power consumption further.

Most tree topology protocols are multi-hop topology protocols, which are famous for the energy saving in the data gathering and transferring. Compared with the traditional wireless network protocols, they greatly reduce the overall energy consumption and prolong the network lifetime. They are widely used in the deployment schemes of wireless sensor networks. During the work of the tree topologies, random links among the nodes take place inevitably for the influence from some interference factors, which incur drastic varieties of the network characteristics. The disorder which comes from the random links influences the network characters of wireless sensor networks greatly.

The rest of the paper is organized as follows. The background of small worlds is first introduced in Section2. The analysis and simulation of the small world phenomena in the tree topologies are proposed in Section 3. The time synchronization characteristics of the small worlds in the tree topologies are analyzed in details in Section 4. Two novel protocols, LEACH-SW and TREEPSI-SW, are proposed as well in this part. The paper concludes in Section 5.

2 SMALL WORLDS

The small world phenomena were first investigated in the sociology that individuals are often linked by a short chain of acquaintances. S. Milgram and his group conducted a series of mail delivery experiments and found that an average of 'six degrees of separation' exists between senders and receivers [8]. D. J. Watts and S. Strogatz proposed an alternative model for the small world phenomena by using the graph theory [9,10]. Recent researchers have shown that the small world phenomena are ubiquitous in nature, society and technology. Small worlds were also observed in the context of the world wide webs [11] and wireless networks [12]. The topologies of wireless sensor networks do not belong to the category of relational graphs. So the α-model [10], which falls into the category of sociology, can't be used directly to analyze the small world characteristics of wireless sensor networks. In fact they belong to the category of spatial graphs, where the link between two nodes depends on the node's radio range and the distance between two nodes.

Some novel topologies and deployment schemes of the sensor nodes, which are based on small worlds, have attracted much attention. One topology optimization method for the urban traffic sensor network was proposed by J. M. Hu et al. [13]. Small world theory was used to improve the performance of the wireless communication system with a heterogeneous transmission model and an optimal transmission radius. One group-based key predistribution scheme which enabled any pair of sensors to establish a unique shared key was proposed by Y. T. Hou et al. [14]. The key path establishment used only local information with logarithmic memory overhead to the number of groups.

3 THE ANALYSIS AND SIMULATION OF SMALL WORLDS IN THE TREE TOPO LOGIES

The small world phenomena exist in the tree topologies during the work of the network, suffering from the influence of some random factors. Obstacles, adjustments of the radio energy, joins of new members and errors of the location precision all incur the link rewiring or the link addition in the tree topologies. The characteristic path length and the clustering coefficient vary according to the variety of the link rewiring or the link addition probability.

The characteristic path length, or the average distance in the entire graph, denoted by $L(G)$, is the median of the average path lengths between any two vertices of the graph G. Since any vertex i in the connected graph G of size n can reach any other n-1 vertex, an average distance between i and any other vertex j, denoted by $L(i)$, is given by the following equation

$$L(i) = \frac{\sum_{j \in V(G)} d(i,j)}{n-1}, \tag{1}$$

where $V(G)$ is the set of the vertices of the graph G, $d(i,j)$ is the distance between vertex i and vertex j. The characteristic path length $L(G)$ in the connected graph is computed from the median of $\{L(i),\ i=1,2\ldots n\}$. The characteristic path length reflects the global structure of a network graph.

The clustering coefficient, denoted by C, indicates what proportion of the neighborhood of vertex i ($\Gamma(i)$) is adjacent to each other. Let the number of edges in the neighborhood of vertex i be $|E(\Gamma(i))|$. Each vertex i has a number of edges, or degree k_i, the total number of possible edges in $\Gamma(i)$ is $\begin{pmatrix} k_i \\ 2 \end{pmatrix}$. Only those vertices in the neighborhood that have at least two edges are included. The clustering coefficient of vertex i is given as follows:

$$C(i) = \frac{|E(\Gamma(i))|}{\begin{pmatrix} k_i \\ 2 \end{pmatrix}}, \quad \forall i \in V'(G), \tag{2}$$

where $i \in V'(G) \equiv \{i \in V(G),\ k_i \geqslant 2\}$. The clustering coefficient C of the whole graph, or network, is the proportion of total actual connections within all vertices' neighborhoods relative to all possible connections between vertices in the graph. The value of C should be equal to the averaged $C(i)$ for each vertex in the graph. C=0 would imply an empty graph and mean that no neighbor of any vertex i is directly connected to any other neighbor of i. On the other hand, C=1 would imply a complete $\frac{n}{k-1}$ subgraph, or clique, in which every vertex is linked to every other vertex directly. The average degree of all vertices in graph G, denoted by k, is defined as follows:

$$k = \sum_{i \in V(G)} \frac{|V_i(G)|}{n}. \tag{3}$$

The degree of vertex i is $k_i = |V_i(G)|$.

In our experiments, link additions are conducted in the topologies of LEACH and TREEPSI. 1000 experiments are conducted and the results are analyzed. In the figures, the logarithmic coordinate is used for x-coordinate.

In the experiments for the small world phenomena in the LEACH tree, 100 nodes are distributed randomly in a 100×100 rectangle field and no more than 6 cluster-heads are selected out. When the link addition probability p increases from 0 to 1, the variety of the characteristic path length or the clustering coefficient is shown in Figure 1 or Figure 2 respectively.

From Figure 1 we can see that in this distribution situation the characteristic path length $L(G)$ of the graph is 3.65 at the initial state. Then it decreases with the increase of p. When p=1, $L(G)$ is 2.45, which decreases by about 33% compared with the initial value when p=0. When p=0, the graph is a two-dimensional regular graph and it has large characteristic path length. When p=1, the graph transforms into a random graph. At this time the tree understratum can be neglected and it has a small characteristic path length. When $0<p<1$, the state of the graph is between the regular graph and the random graph, and the small world phenomena take place now. When p increases from 0 to 0.1 the characteristic path length of the graph remains unchanged. When p increases from 0.1 to 1 it decreases greatly. From the figure we can see that the characteristic path length of the graph varies mainly when p is between 0.1 and 1.

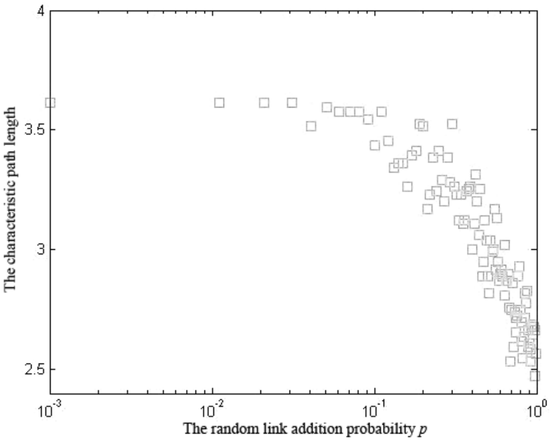

Fig. 1 The characteristic path length of the LEACH tree. If we regard the graph with a large characteristic path length is a 'large' graph and the graph with a small characteristic path length is a 'small' graph, the topology experiences a transformation from a 'large' graph to a 'small' graph with the increase of the link addition probability p. At the same time it transforms from a regular graph to a random graph. This disorder influences the length characteristic greatly

From Figure 2 we can see that the variety of the clustering coefficient of the LEACH tree. The clustering coefficient of the graph is 0 at the initial state for the special topology structure. It increases in the main trend when p increases. When p increases from 0 to 0.1 the clustering coefficient of the graph remains unchanged. When p increases from 0.1 to 1 it increases greatly. The clustering coefficient of the graph varies mainly when p is between 0.1 and 1 as well.

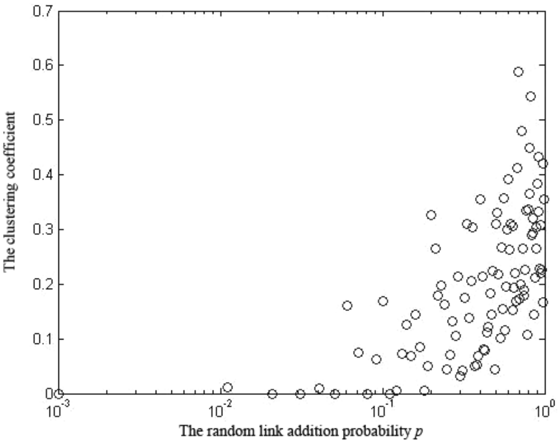

Fig. 2 The clustering coefficient of the LEACH tree. Different from the ring understratum, the clustering coefficient keeps on increasing when p is between 0.1 and 1. The graph transforms from a regular graph to a random graph in this process. Between the two extremes, the topology is in disorder. Compared with Figure 1, we see that the graph has large characteristic path length like a regular graph and large clustering coefficient like a random graph simultaneously in the middle state. The graph transforms into a small world now

The topology of the LEACH tree is a regular graph, which constructs a two-hop tree. For the member node, or the leaf node, its degree is 1 in the regular graph. The degree of a cluster-head node is m+1 (m is the number of member nodes in its cluster). The degree of the base station is w (w is the number of cluster-heads). The clustering coefficient of every node is 0 because no neighbor of any node i is directly connected to any other neighbor of i. Then the clustering coefficient C of the regular graph is 0. The base station is a key point in the topology, without which the regular graph transforms into a forest.

The experiment results show that the small world phenomena exist in the LEACH tree, and the characteristic path length or the clustering coefficient suffers from the influence of the random link addition. How about other tree topologies with multi-hop, multi-cluster and plenty of branches? The TREEPSI tree is such a tree. Some random factors influence its links and it falls into the disorder sometimes.

In the next experiment, 1000 nodes are distributed in a 1000×1000 rectangle field. TREEPSI is conducted and a multi-hop tree topology is constructed. Suffering from the influence of some random factors, the small world phenomena exist during the work of the TREEPSI like LEACH. The link rewiring or the link addition takes place; they come from the communication between the parent node and its children nodes or two children nodes.

Figure 3 shows the variety of the characteristic path length of the TREEPSI tree when p increases from 0 to 1. When p=0, the characteristic path length of the graph is 5.75, and it is a regular graph now. When p=1, the characteristic path length of the graph is 3.15, which decreases by about

45% compared with the value when p=0, and now it becomes a random graph. The tree understratum can be neglected when p=1. The characteristic path length keeps decreasing when p increases.

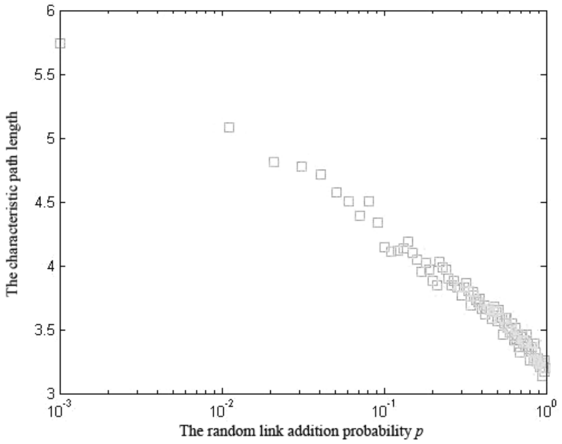

Fig. 3 The characteristic path length of the TREEPSI tree. The topology experiences a transformation from a 'large' graph to a 'small' graph with the increase of the link addition probability p. It transforms from a regular graph to a random graph

When p=0, the clustering coefficient of the TREEPSI tree is 0. When p increases from 0 to 1, the clustering coefficient increases greatly. Figure 4 shows the increasing process during the increase of p.

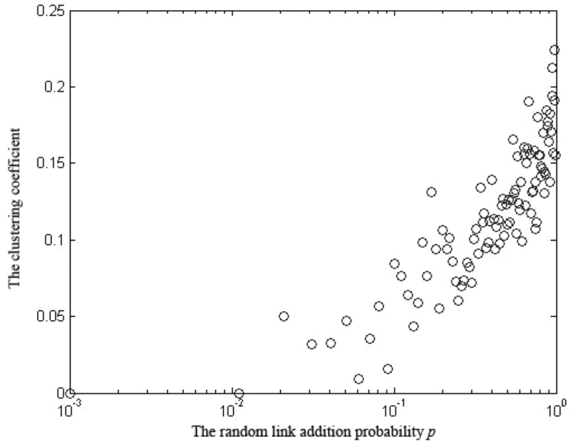

Fig. 4 The clustering coefficient of the TREEPSI tree. The clustering coefficient increases clearly with the increase of the link addition probability p. For a multi-hop and multi-cluster topology, the increase is obviously. Compared with Figure 3, we see that the graph has large characteristic path length like a regular graph and large clustering coefficient like a random graph simultaneously when p is between 0.1 and 1. The graph transforms into a small world now

The above experiment results show that the small world phenomena exist in the TREEPSI tree as well.

The tree topologies are common in the deployment of wireless sensor networks. Under the influence of random interferences, the small world phenomena are ubiquitous in the tree topologies.

4 TIME SYNCHRONIZATION

The time synchronization error depends on the length characteristic of the wireless sensor network. We instinctively deem that the variety of the characteristic path length will influence greatly the time synchronization characteristics of the sensor network. Many time synchronization algorithms for the wireless sensor networks have been proposed over the years. Among these algorithms, RBS (Reference-broadcast synchronization) [15] and TPSN (Timing-sync protocol for sensor networks) [16] are widely discussed. We study their characteristics in the small worlds of the tree topologies.

4.1 RBS and TPSN

Random events, which lead to asymmetric round-trip message delivery delay, contribute directly to synchronization error. The sources of a message's latency includes *send time*, *access time*, *transmission time*, *propagation time*, *reception time* and *receive time*[16].

The fundamental property of RBS is that it synchronizes a set of receivers with one another. The nodes periodically send messages to their neighbors using the network's physical-layer broadcasts. Recipients use the message's arrival time as a point of reference for comparing their own clocks.

The synchronized time error is analyzed in [16]. If two nodes A and B receive the common packet at $T2$ and $T3$ from node C at time $T1$, the following equations can be obtained:

$$T2 = T1 + S_c + P_{C->A} + R_A + D_{t1}^{C->A}, \tag{4}$$

$$T3 = T1 + S_c + P_{C->B} + R_B + D_{t1}^{C->B}. \tag{5}$$

S_C is the time for node C to send the packet, which includes *send time*, *access time* and *transmission time*. R_A is the time for node A to receive the packet, which includes *reception time* and *receive time*, and R_B has the similar meaning. $P_{C->A}$ is *propagation time* between node C and node A, and $P_{C->B}$ has the similar meaning. $D_{t1}^{C->A}$ is the drift between node C and A at time $t1$, and $D_{t1}^{C->B}$ has the similar meaning. Node B sends its timestamp information in $T3$ to node A, and A receives it in $T4$. Then node A calculates the drift $D_{t4}^{A->B}$ between A and B as follows:

$$\Delta = T3 - T2, \tag{6}$$

$$= (P_{C->B} - P_{C->A}) + (R_B - R_A) + (D_{t1}^{C->B} - D_{t1}^{C->A}), \tag{7}$$

$$D_{t1}^{C->B} - D_{t1}^{C->A} = D_{t1}^{A->B} = D_{t4}^{A->B} + RD_{t1->t4}^{A->B}, \tag{8}$$

where $RD_{t1->t4}^{A->B}$ is the relative drift between node A and B from $t1$ to $t4$. The synchronized time error can be calculated as follows:

$$Error = \Delta - D_{t4}^{A->B} = P_D^{UC} + R^{UC} + RD_{t1-t4}^{A-B}, \tag{9}$$

where $P_D^{UC} = P_{C->B} - P_{C->A}$ and $R^{UC} = R_B - R_A$.

In a multi-hop network structure, each conversion step may independent introduce the synchronization error in RBS. According to the research in [15], the average path error for an n-hop path is $\sigma\sqrt{n}$ if the average per-hop error along the path is σ.

TPSN works in two phases, the level discovery phase and the synchronization phase. In the former, a tree hierarchical structure is established in the network. In the latter, a pair wise synchronization is performed along the edges of this structure to establish a global timescale throughout the network. TPSN is suitable especially for the tree topologies of wireless sensor networks; the construction of the tree topology and the time synchronization can be conducted at the same time.

If node A sends a packet to node B at time $T1$, and B receives it at time $T2$. Then at time $T3$ B sends back a reply, and node A receives it at $T4$. The following equations can be derived:

$$T2 = T1 + S_A + P_{A->B} + R_B + D_{t1}^{A->B}, \tag{10}$$

$$T4 = T3 + S_B + P_{A->B} + R_A - D_{t4}^{A->B}, \tag{11}$$

where $D_{t1}^{A->B} = D_{t4}^{A->B} + RD_{t1->t4}^{A->B}$

$$2\Delta = (T2 - T1) - (T4 - T3) \tag{12}$$

$$= S^{UC} + P^{UC} + R^{UC} + RD_{t1->t4}^{A->B} + 2D_{t4}^{A->B}, \tag{13}$$

$S^{UC} = S_A - S_B$, $R^{UC} = R_B - R_A$ and $P^{UC} = P_{A->B} - P_{B-A}$ in above equations.

The synchronized time error can be calculated as follows:

$$Error = \Delta - D_{t4}^{A->B} \tag{14}$$

$$= \frac{S^{UC}}{2} + \frac{P^{UC}}{2} + \frac{R^{UC}}{2} + \frac{RD_{t1->t4}^{A->B}}{2} \tag{15}$$

The error over multi-hop is independent and the worst-case mean error for an n-hop network will be 2×n times more in RBS as compared to TPSN.

4.2 Time Synchronization Characteristics in Small Worlds of the Tree Topologies

The length characteristic of the network plays an important role to the time synchronization characteristics. For the existence of the small world phenomena in the tree topologies, the time synchronization error suffers from the influence of the random link rewiring or the random link addition. The following experiments show this influence. 1000 times of experiments are conducted and the results are analyzed.

If the network is implemented with RBS and the average per-hop error along the path is σ, Figure 5 (a) shows the variety of the ratio of average time synchronization error to σ in the LEACH tree under the influence of the random link addition. From the figure we can see that the initial ratio is 1.9 when p=0. When p=1, the ratio reduces to be 1.55, which decreases by about 18.4% compared with the value when p=0. The ratio decreases drastically when p increases from 0 to 1. It implies that there is a large time synchronization error in a regular network, while there is a small time synchronization error in a random network, where the understratum can be neglected. In the small world network the time synchronization error decreases in the main trend when the random link addition probability increases.

If the network is implemented with TPSN and the average per-hop error along the path is σ, Figure 5 (b) shows the variety of the ratio of average time synchronization error to σ in the LEACH tree. For the tree hierarchical structure, the time synchronization error of TPSN is measured referring to the root node (the base station node) according to its special synchronization procedure. The initial ratio is 0.696 when p=0. When p increases to 1, the ratio decreases to be 0.685, which decreases by about 1.58% compared with the value when p=0. The big trend indicates the decrease of the time synchronization error when p increases.

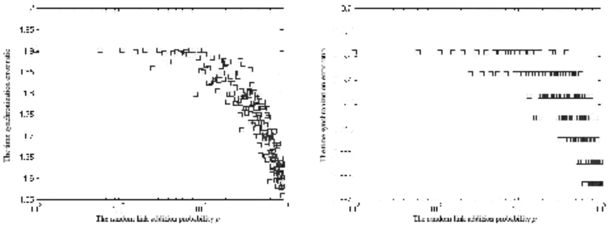

Fig. 5 (a) The time synchronization error ratio of RBS in the LEACH tree. It relies on the length characteristic of the network. With the decrease of characteristic path length, the time synchronization error ratio decrease simultaneously Fig. 5 (b) The time synchronization error ratio of TPSN in the LEACH tree. The synchronization error is measured referring to the root node

The time synchronization error of the TREEPSI tree reflects the similar characteristics with that of the LEACH tree. When p=0, the ratio of average time synchronization error to σ is large. When p increases, the ratio keeps decreasing. When p=1, the graph becomes a random graph and it has a small time synchronization error. Figure 6 (a) and Figure 6 (b) show the varieties of the ratio of average time synchronization error to σ in the TREEPSI tree under the influence of the random link addition. Figure 6 (a) shows the variety of the ratio of average time synchronization error to σ when the network is implemented with RBS. The ratio is 2.4 when p=0, and it is 1.75 when p=1, which decreases by about 27% compared with the value when p=0. Figure 6 (b) shows the variety of the ratio of average time synchronization error to σ when the network is implemented with TPSN. The ratio is 0.865 when p=0, and it is 0.705 when p=1, which decreases by about 18.5% compared with the value when $p=0$.

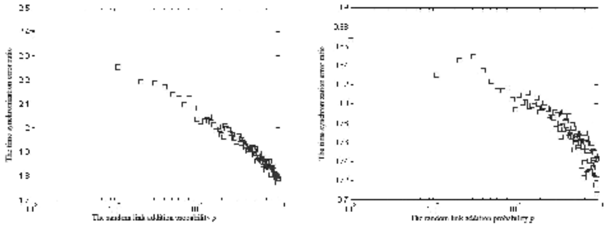

Fig. 6 (a) The time synchronization error ratio of RBS in the TREEPSI tree. With the decrease of characteristic path length, the time synchronization error ratio decrease simultaneously Fig. 6 (b) The time synchronization error ratio of TPSN in the TREEPSI tree. All the nodes can synchronize their local clocks to the root node in the multi-hop and multi-cluster network. The error is measured referring to the root node and it relies greatly on the length characteristic of the network. In this disorder network, the time synchronization error varies with the probability p. A global timescale throughout the network is established.

From above analysis we can see that the small world characteristics in the tree topologies of wireless sensor networks affect the time synchronization results greatly. The existence of some random factors brings impacts to the time synchronization characteristics of the network drastically. The time synchronization error decreases with the increase of the random link rewiring or the random link addition probability in the main trend. Random factors exist in the wireless sensor network ubiquitously and their influences on the time synchronization play an important role in the work of network. We use the analysis results to improve the time synchronization algorithms or the network protocols.

4.3 Novel Protocols Based on Small Worlds

The small world characteristics are considered to be used for reducing the time synchronization error and improving the performance of the sensor network. Two novel protocols named LEACH-SW (LEACH based on Small Worlds) and TREEPSI-SW (TREEPSI based on Small Worlds) are proposed for the purpose.

LEACH-SW also includes two phases: a cluster formation phase and a cluster steady phase in every round. In the cluster formation phase, a certain number of cluster-heads are selected out. Each sensor node chooses the nearest cluster-head as its own parent node. Once all the nodes are organized into the tree topology, the time synchronization process is conducted. At the same time the link rewiring or the link addition is added to the tree topology with a random probability p, $0.1<p<1$. For the influence of small world characteristics, the time synchronization error can be reduced greatly. After a certain time the process of the link rewiring or the link addition ends, and the network returns to the regular state. Each cluster-head creates a TDMA schedule for all the members in its cluster. In the steady phase of LEACH-SW, the member nodes collect the data from the physical environment and send them to their cluster-heads. Once the cluster-heads receive all the data in a frame, they perform data aggregation to enhance the useful signal and reduce the uncorrelated noises. Then the cluster-heads transmit them to the base station directly. The radio of each member node is turned off until its allocated transmission time slot in order to reduce energy consumption.

TREEPSI-SW (TREEPSI based on Small Worlds) is also proposed, similar technologies are used to reduce the time synchronization error like LEACH-SW. The time synchronization process is conducted once all the nodes are organized into the tree topology. At the same time the link rewiring or the link addition is added to the topology structure with a random probability p, $p>0$. For the influence of small world characteristics, the time synchronization error can be reduced greatly. After a certain time the process of the link rewiring or the link addition ends, and the network returns to the regular state. The base station collects data from the sensor nodes in two ways. On one hand, the root node initiates data gathering process by broadcasting a small control packet towards the children nodes using any standard tree traversal algorithm. On the other hand, the TDMA or the CDMA scheme is taken into use by the tree topology to avoid collision among the nodes, and all the children nodes send information to their parent nodes. The parent nodes process the received data with their own and transfer them upwards along the branches of the tree. The process is repeated till the root node receives the data, which are processed and transmitted directly to the base station.

5 CONCLUSION SAND FUTURE WORK

The tree topology is a kind of frequently used architecture, which is ubiquitous in the deployment of wireless sensor nodes. Because of the existence of some random factors, the link rewiring or the link addition takes place universally. In this paper, the small world phenomena in the tree topologies are studied. The characteristic path length and the clustering coefficient of the topology vary drastically with the variety of the link rewiring or the link addition probability. In the further study, the variety of the characteristic path length affects the time synchronization characteristics of the network greatly. The time synchronization error decreases with the increase of the random link rewiring or the random link addition probability in the main trend. Two novel protocols named LEACH-SW and TREEPSI-SW, which are based on the small world characteristics of the tree topologies, are proposed to improve the performances of the wireless sensor networks. In the future research, we will pay more attention to finding a common navigation algorithm, which runs automatically for searching the short paths in the small worlds of the tree topologies.

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