Power-aware Small World Topology in Ad Hoc Networks

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***Abstract*—Ad hoc network is a popular research topic in wireless network recently. It has good performance on the robustness and dynamics, such as minimal configuration and quick deployment for emergency situations. However, the ad hoc network also suffers from the limited power source provision because of its fundamental architecture. Therefore, the power issue becomes one of the most important concerns in ad hoc networks. In this paper, we propose to build a small world topology in the ad hoc networks as a topology control method to solve the power issues. Following the rule of small world topology, we manually construct a self-adjust power-aware small world network by implementing the decision method for random probability and action protocols to decrease the power consumption. Although this work is not the optimal solution to save power consumption in ad hoc networks, it can achieve a tradeoff between transmission efficiency and power consumption. And the self-adjustment feature of the small world topology can also facilitate the performance to prolong the lifetime of whole ad hoc network.**

***Index terms*—Ad Hoc Networks, Small World Topology, Random Probability, Head Node, Inner Node, Self-adjustment**

I. Introduction

The concept of commercial ad hoc networks arrived in the 1990s with notebook computers and other viable communications equipment, and it becomes a quite popular research topic recently. The history of ad hoc network can be traced back to 1972, and the DoD-sponsored packet radio network (PRNET) evolved into Survivable Adaptive Radio Networks (SURAN) program in the early 1980s. Ad hoc networks are suitable for use in situations where infrastructure is either not available, not trusted, or should not be relied on in times of emergency. A few examples include: battlefield; sensors scattered throughout a city for biological detection; an infrastructure less networks of notebook computers in a conference or campus setting; rare animal tracking; space exploration; undersea operations; and temporary offices such as campaign headquarters. It needs minimal configuration and can be quickly deployed for emergency situations.

The wireless ad hoc networks – also called WANET sometimes—are made up of a group of mobile units equipped with radio transceivers that wish to communicate with each other over wireless channels. The nodes in a WANET relay information for each other in a multi-hop fashion, as a centralized authority is absent. In this way, nodes in a WANET are self-organized to form a decentralized communication network that does not rely on any fixed infrastructures. The network is dynamic with nodes leaving and joining at any time. However, for a fixed instant of time, the wireless ad hoc network can be modeled as a graph where the number of neighbors that a node can establish wireless links to is known as the node degree. Being constructed mostly of battery operated devices, the capacity and lifetime of wireless ad hoc networks can be surprisingly low. For this reason, power efficiency is a very important consideration in designing ad hoc networks.

In this scope, we design an ad hoc network using small world topology, known also as “six degrees of separation” [1], to achieve power-efficient performance. We manually construct a self-adjust power-aware small world network by implementing the decision method for the random probability and action protocols to decrease the power consumption. This design can achieve a tradeoff between transmission efficiency and power consumption, thereby prolonging the lifetime of whole ad hoc network without much efficiency loss.

The rest of this paper is organized as follows: the Section II will show some related work on the power related technologies in ad hoc networks and the former researches of small world networks. Then in Section III we will implement our small world topology with power concerns in ad hoc networks. The simulation experiments and discussion will be described in Section IV. And the Section V will state the conclusion and the future work for this paper.

II. Related Work

Being limited by the transmitter power of nodes and available energy resources, it is very important for ad hoc

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networks to adopt energy efficient strategies to maximize network lifetime. As S. Mahfoudh and P. Minet mentioning in their survey [20], there are generally four primary ways to realize the goal of saving energy in ad hoc networks. In this paper, we mainly focus on the topology control methods. Many topology control algorithms have been proposed to reduce energy consumption and improve network capacity, while maintaining network connectivity. The key idea of topology control is that instead of transmitting using the maximal power, each node adjusts its power transmission. Thus, energy dissipated in transmission is reduced and a new network topology is created. RNG, Related Neighborhood Graphs [2], removes any edge directly connecting two nodes if there is a path of two hops or more between them. MST, Minimum Spanning Tree [3], transforms the network graph in a minimum energy broadcast tree rooted at a given source node giving the shortest path to any other node; only the energy dissipated in transmission is taken into account .LMST, Local Minimum Spanning Tree [4], is a localized minimum spanning tree where each node computes its own MST in its neighborhood and only retains those one hop neighbors in the tree as its neighbor in the final topology. In [5], the idea is to reduce the transmission range of every node to minimize energy dissipated in transmission. However, these algorithms all focus on pure power saving research without considering other important aspects in wireless transmission of ad hoc networks.

To have a wider concern on system performance, other important features should be involved, and even to achieve tradeoff among them. For example, in [6], the TCH (Topology Control with Hitch-hiking) is used to obtain a strongly connected topology minimizing energy dissipated in transmission with partial signals. It not only does consider the power issues, but also involves the topology connection as a important part in research. In [7], Adaptive Transmission Power Control (ATPC), is proposed which allows each node to know the optimal transmission power level to use for each neighbor while maintaining a good link quality. In this paper, we concern the additional feature, the performance of efficiency, besides the power consumption. We will use the small world network to implement the topology control to facilitate the performance on power saving and transmission efficiency in ad hoc networks.

The small world phenomenon became famous since the experiment held by Stanley Milgram [8], in which the six degrees of separation is observed. Generally, it is a topology network in which the nodes can connect to any other ones within average limited hops (or paths). In early days, there is much work on the theoretical research of small world. Duncan Watts and Steve Strogatz [9] showed the theoretical description and analysis on the small world network, which is neither completely regular nor completely random, but a case between these two extremes. They also donated some notations such as random probability, path length and cluster coefficient which are very helpful for the research on the small world network. Kleinberg [10, 11] proposes a theoretical framework for analyzing graphs with small world properties. His work reveals that the small world model has two fundamental components: first short chains exist ubiquitously, and second individuals operating with purely local information are very adept at finding these chains.

Recently, there is much research on the practice of small world network. Merugu et al. [12] propose a small world overlay structure on top of an unstructured and decentralized P2P network, while Hui, Lui and Yau [13] implement such a model over the structured and decentralized P2P network. The common feature of both work is to provide a small world topological structure, so as to efficiently look up and transfer resources in P2P systems. Xia et al. [18] designed SW-R2P, a trusted small world overlay P2P network with role based and reputation based access control policies, in order to implement an efficiency and security Peer-to-Peer network. All the work above focuses on the small world topology used to solve P2P issues, such as robustness, hop length and reliability. Similarly, there is also some research concerning on small world topology in ad hoc networks. Sonja Filiposka et al. [14] conduct a research on the small world in ad hoc networks which has an extreme influence on enhancing the social characteristics related performance. There is also a small world in motion (SWIM) implemented by Sokol Kosta, Alessandro Mei and Julinda Stefa [15] to improve the performance of the ad hoc mobile networks. Helmy[16] and Dixit et al [17] proposed the construction of wireless ad hoc networks with small average path length by adopting the small world paradigm. However, all the research work above focuses on the feasibility, efficiency and robustness, ignoring the power issues which should be such an important concern in ad hoc networks. In this paper, our model considers the power issue with self-adjustment strategy to achieve tradeoff between efficiency and power consumption.

III. Small World Ad Hoc Network Implementation

The small world topology evolved in ad hoc networks can be shaped as the topology control method going on between clients. It is usually not an inherent paradigm. In order to improve the performance of transmission efficiency, network robustness and power persistency in ad hoc networks, the network topology can follow the principle to be constructed and adjusted as a small world paradigm. Therefore, how to construct and maintain a small world topology in ad hoc networks is the key problem to be solved.

The implementation for the small world ad hoc networks may be different on variable cases. We need to create some principles with which to determine the probability p and the protocols how we can construct the short links and long links. The details will be elaborated to show the implementation of small world ad hoc networks.

A. Preliminary Terminologies

Firstly, we clarify some important notations of the small world network, which can be categorized into link roles and node roles.

The link roles include long link and short link (or inner link). The long link is used to connect different clusters of nodes, and the short link is responsible for the connection in the cluster. The principle for the short link construction is simple, while the principle for the long link construction which is determined by the link probability p is more complex.

The nodes roles include three types of nodes: head node, candidate head node and inner node. The head node takes main responsibility for connecting clusters based on some probability. It is very important in expanding the scale of whole network. The candidate head node is the shadow node of head node, which means it may take the place of head node when the original head node leaves, fails or becomes unaccessible. It is required to backup some data of the head nodes used to recover the network when the head nodes need to be substituted. The inner nodes are the main participants in the cluster. They are connected by short links within the cluster. Based on the requirements of network, we can evaluate the performance of the nodes to determine the head nodes, candidate head nodes and inner nodes.

B. Principle to determine probability p

The first step in small world network implementation is to determine the probability p for long link creation. We set the requirements or the concerns of network, and formulate functions for them as parts to construct the probability p. They have different scales which need to be mapped to a consistent range. Finally we add them after multiplying corresponding weights. The formula is defined as follows.

$$p = F(w_1 f_1(x_1) + w_2 f_2(x_2) + w_3 f_3(x_3))$$
(1)

After determining the principles and functions to calculate the probabilities, as the second step, head nodes can evaluate their long link probabilities with nodes in other clusters. Choosing proper nodes to build a long link expands the scale of small world network. The head node will calculate the probability p based on its prefetched knowledge, and decide the long link state with that probability. As a simple implementation, we will randomly generate a number, if it is in the range of the probability, then we build the link, otherwise we will not. We may also update the probability if it is necessary, while the network is running.

We use a simple decision model for the probability p in our power-aware small world. It is consist of multiple facets, including the power condition (PC), the number of Links held already (LN), the distance to the target nodes (ND), and an overall decision (OD) for the probability p. Figure 1 shows the model structure.

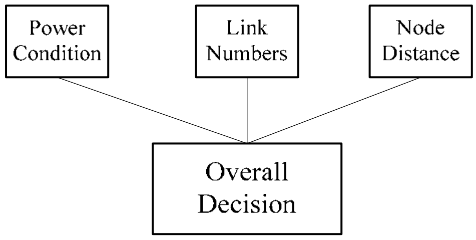

Figure 1. Decision model specialized for power-aware small world ad hoc networks

- PC is the metric denoting the power condition of nodes, mostly head nodes. It can be calculated automatically in the intercommunication between nodes. We formulate it as $PC = Power_{current} / Power_{full}$ where $Power_{current}$ and $Power_{full}$ are the power values for current condition and full-charged condition. In this way, we normalize the PC of devices in ad hoc networks to the range from 0 to 1.
- LN is the metric denoting the long link numbers which nodes hold in the interaction. This metric is included for taking a consideration in power saving. If the node holds enough long links, we need not to build other long links to expand the range as well as the power. The normalizing for LN is not as simple as PC, in which we formulate a function mapping link numbers to the range from 0 to 1. The function should be defined as mapping link number 0 to value 1, and through the link numbers increasing, the values are more close to 0. Finally, we choose the exponentially decreasing function $LN = k^{-x}$, in which k is a real number greater than 1. We can choose a proper k for a corresponding application depending on its scale of ad hoc network and expectation of long link number.
- ND is the metric denoting the distance of two nodes in the interaction. It is significantly related to the power consumption through the inverse square law, $E \propto I / d^2$. The normalizing function should maintain the relationship between the power and the distance, and is better to be practical. We finally choose $ND = (d_0 / d)^2$, where d_0 is the distance to the closest node which is not in the cluster. This is reasonable because the closest one out of the cluster is the most power efficient node to link, which should be mapped to the largest value 1 for the distance.
- OD is the final result of the decision network, which comprehensively evaluates all the leaf metrics introduced above. We can calculate it by the function $OD = W_{PC} * PC + W_{LN} * LN + W_{ND} * ND$, where W_{PC} , W_{LN} , and W_{ND} are the weights to the metrics respectively, and $W_{PC} + W_{LN} + W_{ND} = 1$. The weights can simply be determined by the head node of the cluster according to its practical concerns. OD is regarded as the probability which head node uses to create long links to other cluster. The head nodes

hold OD instances for corresponding clusters, which will be applied to some key operations, such as maintaining the node list for long links, searching new nodes for routing, etc.

This model design for the ad hoc networks depends on their properties that the nodes can be both routers and terminators. Therefore, we can design a principle for each single node, and drive the network topology evolving into a small world network.

The probability implementation is treated as the evaluation in multiple differentiated power aspects of nodes. It can be customized by adding new aspects or constructing a more complicated decision network topology. During the network construction or data transmission, the resource providers can be selected based on their trust evaluations. The requester can combine several aspects of the candidate providers into the overall probability which decides to create appropriate long links. For example, the boundary case is that when the header node's PC is full and its LN is zero, if it can find the closest node to it, there is no reason to reject that link. And in this case, the probability for that decision model is just 1.

C. Criteria for head node

When a new node joins one of the clusters in the network, it is necessary to determine its role in the cluster, head node, candidate head node or inner node. We will show criteria for the cluster to choose the head node and candidate head node. The criteria is used to judge whether the node can afford to play the role as the head nodes based on its power related and other properties. The criterion function is as following:

$$C(node) = w_1 Power(node) + w_2 Seen(node) + w_3 Range(node) \quad (2)$$

In this function, *C()* is the overall evaluation for a node, and w_1, w_2, w_3 are weights for different concerns. The *Power()* represents the node's power capability, the *Seen()* is the number of other nodes covered with by the node under its maximum radio, and the *Range()* is the maximum range that the node can reach.

As following the function above, the original ad hoc network may gradually evolve to a small world ad hoc network. Furthermore, to achieve the power-aware small world implementation, we still need to design specific protocols about the action on the nodes and links.

D. Protocols Implementation

In this section, we will describe protocols for building and maintaining the power-aware small world topology in ad hoc networks. The action protocols are specifically for the events of node joining a cluster, leaving a cluster and failing.

(1) Node Join Protocol (NJP)

If node i requires to join a cluster g, we need to determine its role in the network. For a rookie node, which means it has no interaction with any other node or it transfers from one cluster to another cluster, the node can only use its criteria value in the cluster g to evaluate its capability for node role. By comparing the criteria value of node i with j which takes a special node role in a cluster, such as the head node or the candidate head node, we can determine the node role of i. If the value of node i is greater than j, i will join the cluster g and replace the role of j to be a head node or a candidate head node. Otherwise, j will keep its role and i will be set as the inner node.

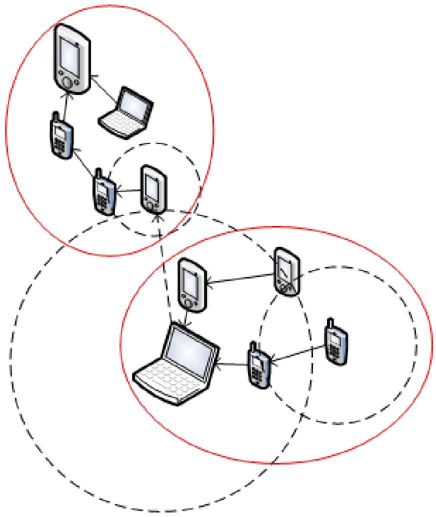

Figure 2. Short link construction for a new joining

However, before the node i sends the criteria, it firstly needs to construct the short links to reach other nodes. In the short link construction, we achieve a method which can avoid the power law phenomenon and have a benefit to save power based on the small world. The short links in this protocol are not simply connected to the head nodes. If a node i joins the network, it will increase the range to find a head node, or node which can reach the head node in limited hops (2 or 3 hops) as Figure 2 shows. Then it will join the cluster g of that head node, and send its criteria value to determine its role.

The algorithm of the node join protocol is specified in Algorithm 1 below.

Algorithm 1: Node Join Protocol

INPUT i : joining node; g : joined cluster;

j : special role node of g

OUTPUT g' : the new cluster i joins

GL_i =Initialize(i) //initialize i 's short links

R_i = inner node of g // initialize i 's role as inner node

$g' = g + i$ // add node i to cluster g

$C(i) = w_1 Power(i) + w_2 Seen(i) + w_3 Range(i)$ // calculate i 's value

If $C(i) > C(firstCandidateheadnode)$:

For all head node j

$C(j) = w_1 Power(j) + w_2 Seen(j) + w_3 Range(j)$ // calculate j 's value

If ($C(i) > C(j)$)

R_i = head node of g //set i 's role as head node
GL_i += Update(GL_j) //add possible short links to i
LL_i = Update(LL_j) //set i 's long link
GL_j = initialize(j)
break
Else
GL_j += short link to i //add a short link from j to i
EndIf
Endfor
Else
For all candidate head node j
$C(j) = w_1 Power(j) + w_2 Seen(j) + w_3 Range(j)$
// calculate j's value
If ($C(i) > C(j)$)
R_i =candidate head node of g // set i as candidate
$data(LL_i)$ = $\mathrm{Replicate}(data(LL_j))$ // copy j's long link data
Message(Head node, R_i) // update i 'role in cluster
break
EndIf
Endfor
Endif
Output g'

(2) Node Leave Protocol (NLP)

When a node i leaves the cluster g , it performs differently according to its role. If it is a head node, the first mission it should complete is to find a substitutor node j in its cluster g , which holds the evaluation closest to i . In our algorithm, to find such a node is similar to choose the candidate head node. Head node i sends a message to all the other nodes in its cluster, notifying that leaving the cluster and choosing the candidate head node j as the new head node. Then all the nodes in the cluster will calculate their hops to the new head node to adjust their short links. The new head node usually holds a replicated data from the former head node. It can update those data and replicate them to a new candidate head node. The nodes which originally have short links to that leaving head node need to modify its range and rearrange their short links.

There are two situations for i to leave the cluster g , which are i just leaving the network and i joining another cluster in the network. If the cluster g contains only one node i and i leaves the network, the cluster is eliminated from the network straightforwardly. If the cluster g contains more than one nodes and the substitutor j is picked out, it needs to complete the whole process for the head node leaving. In the other situation, if i leaves the cluster g and joins another cluster, the implementation of the leaving part is almost the same as the first situation, and the implementation of the joining part can be handled by NJP.

We implement the node leave protocol in such a way that it can keep the whole system stable and consistent. Its algorithm is introduced in detail as following.

Algorithm 2: Node Leave Protocol

INPUT i : leaving node; g : i 's cluster
j : candidate head node of g
OUTPUT g' : the cluster i leaves; g'' : the cluster i joins
If ($sizeof(g) == 1$) // cluster g contains only one node
g' = NULL // cluster g is set empty
If ($Action(i)$ == "join another cluster") // i joins another cluster
NJP (i , g'') // apply node join protocol to i joining g''
Endif
Else // cluster g contains more than one node
R_j = head node of g
GL_j += Update(GL_i) // add possible short links to j
LL_j = Update($data(LL_j)$) // set j's long link from its data
Broadcast(i , j) // update other nodes
If ($Action(i)$ =="join another cluster")
// i joins another cluster
NJP(i , g'') // apply node join protocol to i joining g''
$g' = g - i$ // Remove i from cluster g
Endif
Output g' , g''

(3) Node Failure Protocol (NFP)

Each node periodically sends request to the head node of its cluster to state it is alive and to judge whether the head node is alive. If a node i does not respond to other node's request beyond the time threshold, i is considered as a failed node, and the network loses all the information of i . In that case, the network uses the node failure protocol to recover and maintain the remained links.

Supposing the node i is in the cluster g , if g contains only one node i who fails, g becomes empty and is eliminated from the network automatically. The elimination will be detected by other nodes which link to g and remove their corresponding long links later. If there are more than one node in the cluster g and the failed node i is the head node of the cluster, we find a substitutor node j which is the candidate head node in that cluster g . The way to find the node j is the same as to find a substitutor for a leaving node which is specified in NLP. In another situation, if node i is an inner node, then it does not need a substitutor but has to call those nodes which has short link to i to update the short links similar to NLP.

The node failure protocol stabilizes the network when a node failed, and keeps the network robust to various attacks. Algorithm 3 describes NFP.

Algorithm 3: Node Failure Protocol

INPUT i : failed node; g : i 's cluster
OUTPUT g' : the cluster after i is failed and removed
If ($sizeof(g) == 1$) // g contains only one node
  g' = NULL // cluster g is set empty}
Else // g contains more than one node
  If (R_i == "head node") //node i is an head node
    R_j = head node of g
    GL_j += Update(GL_i) //add possible short links to j
    LL_j = Update($data(LL_j)$) //set j's long link from its data
    Broadcast(i , j) // update other nodes
  Else
    Broadcast(i)// update other nodes sent by head node
  Endif
  g' = $g - i$ //Remove node i from cluster g
Endif
Output g'

IV. EXPERIMENTS AND DISCUSSION

A. Simulation Setup

Our simulation experiments are based on rewriting the Matlab simulator Prowler which implements a global topology control and a dynamic node-driven self-adjust topology control.

The Matlab simulator Prowler is deployed on the lab PC as the simulation environment. The PC is set up with Intel Dual Core 2.13GHz and 2G memory. We simulate 100 nodes with different initialized power condition range from 1 to 10. The nodes will be randomly deployed in area, and we assume a consistent distance measure for calculating the power consumption.

B. Experiments

We use three simulation experiments to evaluate the performance of our ad hoc networks in the power-aware small world topology. We compare our model with other topology and routing models, such as spantree and clusterhead gateway switch routing (CGSR) [19]. The spantree model is used to show the advantages of our model on topology-related efficiency. And the power-unaware small world model, CGSR, is chosen to explore the advantage of our model on energy saving for our power-aware small world topology can be regarded as an extension of the CGSR on power concerns and self-adjusting functionality.

(1) Power Consumption

The first experiment is about the power consumption. We design it to compare our model with spantree model and CGSR model. Assuming that a random pair of nodes request for communication continually and a node which relay the communication consumes 1 power, the experiment is designed as that along with the time how much the power of the whole network is consumed. The results are shown in Figure 3, with the time as the x-coordinate and the total power of the network as the y-coordinate.

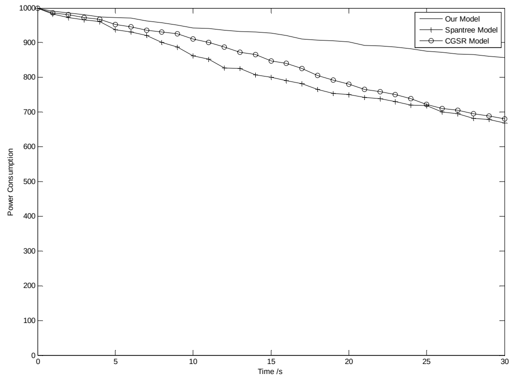

Figure 3. Power consumption experiment on three models

The experimental results show that all three curves decrease, and our small world model decreases more slowly than the other two models. This is caused by that in general our model is a greedy optimal method. We try to minimize the power consumption on every node through choosing proper headnode and links. Even that it has not been proved theoretically our method can achieve global optimal, the experiment still shows its better results than other two models who have no efficient energy control approach.

(2) Average Path Length

The second experiment is about the average path length, which is an important evaluation to compare our model with spantree model and CGSR model. We increase the number of nodes in the network from 50 to 150. Each node randomly chooses another node to communicate with, and we calculate the average path length of the whole network. The results are shown in Figure 4, with the number of nodes as x-coordinate and the average path length as y-coordinate.

From the experimental results, we observe that from 50 nodes to 150 nodes the average path lengths for our model and CGSR model are all less than 5, and their increments also do not exceed 1. However, the compared

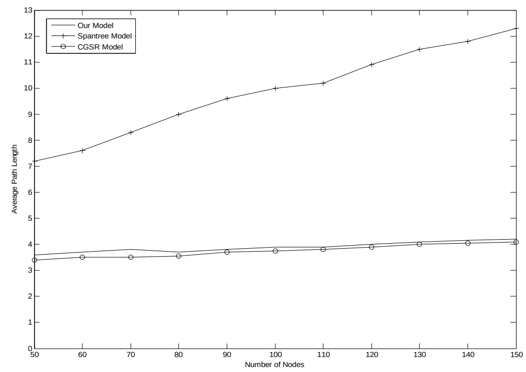

Figure 4. Average path length experiment on three models

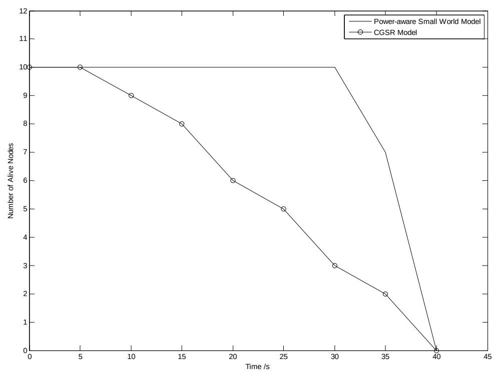

Figure 5. Life time experiment on two models

spantree model has greater lengths and increases much faster. These indicated advantages are mainly brought about by their small world topology. Although the average path length of our model is quite close to CGSR model, it is still a little bit greater than CGSR. This is caused by multihops intra clusters for power concerns.

(3) Life Time

The third experiment is about the life time of the whole ad hoc network. Through this experiment, we want to show that by taking the power condition into the decision model we can keep a power consumption balance among all the nodes, therefore we can keep the life time of the network as long as possible. Our model is compared with the CGSR model, power-unaware small world model. The experiment is designed as that along with the time how many nodes alive in the network. The results are shown in Figure 5, with the time as the x-coordinate and the number of alive nodes in a cluster as the y-coordinate.

The experimental results show that the two models have the same life time, however during the life time the curve of power-aware small world model is more balanced than the curve of power-unaware small world model. This is because the power-aware model can do the self-adjustment based on the power condition of the nodes to make them alive as long as possible. The CGSR model can easily fall into the structure with power law phenomenon, which is good for decreasing hop numbers but is lack for saving and balancing energy consumption in networks, especially for ad hoc network with more stable structure applications. For example, when one head node's power is under the threshold which can be set by the system, our model will choose another node with more power to take the position of head node, and reduce the scale and the links to save the power of the original head node. However, in CGSR model draining out one single node may cause isolated nodes in the ad hoc network and some other related problems.

V. Conclusions and Future Work

In this paper, we use the power-aware small world topology as an adaptive power efficient strategy to maximize network life time and efficiency of the ad hoc networks. We design a kernel decision model for the principles of the random probability and head node determination. We also implement the action protocols, such as the NJP, NLP and NFP with a self-adjustment scheme for the power consumption balance.

Finally, we use the simulation experiments to test the performances on power consumption, average path length and life time. The results show that our model can achieve a tradeoff between transmission efficiency and power consumption, and also hold the self-adjustment feature to facilitate the performance to prolong the lifetime of whole ad hoc network.

For the future work, we may optimize our implementation according to other theories. For example, we can use some more sophisticated approaches such as the Bayesian decision theory to determine the random probability p of the long links. We can also add more action protocols to specify diverse behaviors of the nodes. Finally, we will try to move our implementation from the simulation experiments to the practical applications which can be used to test the feasibility and practicability of our work.

Acknowledgement

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