Adaptive Topology Control for Mobile Ad Hoc Networks

Andy An-Kai Jeng and Rong-Hong Jan, *Senior Member*, *IEEE Computer Society*

Abstract—In MANETs, mobile devices are usually powered by batteries with limited energy supplies. Topology control is a promising approach, which conserves energy by either reducing transmission power for each node or preserving energy-efficient routes for the entire network. However, there is empirically a trade-off between the energy efficiency of the nodes and routes in a topology. Besides, it may consume considerable energy to maintain the topology due to node mobility. In this paper, we propose an adaptive topology control protocol for mobile nodes. The protocol allows each node to decide whether to support energy-efficient routing or conserve its own energy. Moreover, it can drastically shrink the broadcasting power of beacon messages for mobile nodes. We prove that any reconstruction and change of broadcasting radius converge in four and five beacon intervals, respectively. The experimental results show that our protocol can significantly reduce the total energy consumption for each successfully transmitted packet, and prolong the life times of nodes, especially in high mobility environments.

Index Terms—Mobile ad hoc network, topology control, energy-efficient protocol, distributed system.

1 Introduction

The continuing developments in mobile ad hoc networks (MANETs) have led to many available applications in commercial, military, and educational areas. Nodes can communicate through wireless carries without any wired connection, thereby enhancing conventional deployment. However, mobile devices are usually powered by limited energy supplies, where a continuing recharging could be hardly attainable. Hence, a substantial body of research has been devoted to conserving energy in MANETs.

The *topology control* is an important approach to conserving energy [1], which aims at determining a set of wireless links among nodes so as to achieve certain energy-efficient properties. Generally speaking, it can reduce the energy consumption in two ways.

1. *Reduce energy consumption of nodes*. In wireless networks, the power required to transmit from one node to another is considerable, and could be exponentially grown by their distance [2]. Thus, to conserve a node's energy, the *transmission radius* should be confined to cover closer neighbors only in the underlying topology. On the other hand, nodes are responsible for relaying messages in MANETs. If the loads are overly concentrated on a certain node, the node's energy could be quickly drained out. Keeping a lower *node degree* (the number of links connected to a node) can prevent a node from relaying for too many sources [3].
2. *Reduce energy consumption of routes*. In MANETs, communication is typically conducted by relaying messages through some paths. During the relaying process, each node on a path should transmit at sufficient power to cover the next hop. Therefore, the path with smaller total transmission power, called an *energy-efficient route*, should be preserved for any possible communication pair while controlling the topology.

Overall, the energy efficiencies of nodes and routes are equally important. The living time of an individual node can be prolonged, if the node degree (transmission radius) is reduced to consume less energy. Moreover, the total energy consumption for the global wide communication can be saved by preserving more energy-efficient routes. Nevertheless, there is empirically a trade-off. To reduce the transmission radius or node degree, some links constituting an energy-efficient route could be sacrificed.

To address the trade-off, we have proposed a flexible structure, called the *r-neighborhood graph*, in our recent studies [4], [5], [6]. As shown in Fig. 1, given two nodes u and v, and a parameter $0 \leq r \leq 1$, we define the region (the shaded area) intersected by two open disks centered, respectively, at u and v with the radius of their distance $d(u,v)$ and an open disk centered at the middle point m with the radius $l = (d(u,v)/2)(1+2r^2)^{1/2}$ as the *r-neighborhood region* of u and v, denoted as $NR_r(u,v)$. The r-neighborhood graph of a set of nodes V, denoted as $NG_r(V)$, consists of an edge uv if and only if $NR_r(u,v)$ contains no other node in V.

The energy consumption between nodes and routes in this graph can be balanced by adjusting the parameter r. By increasing r, the radius and degree of each node become smaller. On the contrary, more energy-efficient routes can be found by reducing r. In particular, when $r=1$ the node degree is not greater than 6, and the optimal energy-efficient routes are preserved when $r=0$. More importantly, each node can asynchronously determine its links in this graph using the positions of its one-hop neighbors. In other words, the construction is *fully distributed* and *localized*.

• *The authors are with the Department of Computer Science, National Chiao Tung University, Hsinchu 300, Taiwan, R.O.C.*
E-mail: {andyjeng, rhjan}@cis.nctu.edu.tw.

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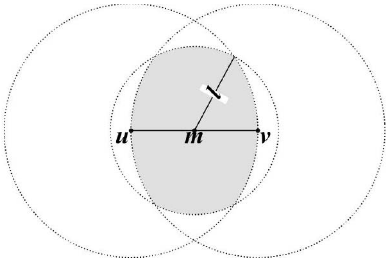

Fig. 1. The r-neighborhood region of u and v.

However, the r-neighborhood graph was primarily designed for stationary nodes. When applied to mobile environments, more attention should be paid to nodes' mobility. Besides, for theoretical interest, the power consumption model was simplified in our previous works. The simplification may overlook some facts in reality. For these reasons, our goal is to extend the concept of the r-neighborhood graph to a more realistic network. To achieve this purpose, we make the following contributions in this paper.

1. *Generalized power consumption model*. In [4] and [5], we assumed the power consumed at the receiver is negligible. Besides, the path loss is specific to free space environments, where no obstacle or reflection exists. In this paper, we generalize the r-neighborhood graph to a more realistic power consumption model proposed by Rodoplu and Meng [7]. Both the receiving cost and the general path loss exponent are considered in this model.
2. *Extended parameter set*. Although the energy consumption can be adjusted through the parameter r, the desired value of r would be varied for different nodes. For example, a node with less energy would prefer a larger r to reduce its own transmission radius or node degree, while a smaller r would be preferred, if the node has surplus energy to perform relaying for other communication pairs. In other words, an identical r cannot provide the most appropriate settings for all nodes. Therefore, we extend the r-neighborhood graph so that each node u has the flexibility to configure its own r_u.
3. *Energy-efficient maintenance protocol*. To maintain the topology for mobile nodes, each node has to periodically broadcast a beacon to denote its new position. It may consume considerable energy, if the broadcasting power is large. We design an energy-efficient maintenance protocol, named the *Adaptive Neighborhood Graph-based Topology Control (ANGTC)*. The *ANGTC* can drastically shrink the broadcasting power for each periodic beacon. Moreover, we prove that any reconstruction can be done in 4Δ, where Δ is the beacon interval.
4. *Adaptive configuration rule*. In [6], we turned the value of r to find the minimal energy consumption using simulation. But there was no discussion about how to adjust r in a decentralized matter. Moreover, the settings of different r_u's could be more complicated. Therefore, this paper proposes an adaptive configuration rule inside the ANGTC to configure the parameter r_u for each node u. The rule aims at achieving balanced energy consumption between nodes and routes, and improving the stability of the topology.

For a detailed introduction to the r-neighborhood graph and its challenges in mobile environments, readers can refer to Appendices A.1, A.2, and A.3, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68.

The rest of this paper is organized as follows: Section 2 specifies the network model and measurements. Section 3 defines the graphic structures and analyzes their properties. The protocol and configuration rule are investigated in Sections 4 and 5, respectively. Section 6 presents a series of simulation results. Concluding remarks are given in the last section. The proof of any property shown in this paper can be found in Appendix F, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68.

2 Network Model and Measurements

Given a deployment region $\aleph$, a set V of n nodes is distributed on $\aleph$. Each node $u \in V$ can obtain its location $Loc(u)$ on $\aleph$ using a lower power GPS. Besides, the power consumption follows the *path loss model* [2]. More specifically, let $p_{max}(u)$ denote the maximum transmission power of a node u. Node u can transmit to another node v only if $td(u,v)^\alpha \le p_{max}(u)$, where $d(u,v)$ is the euclidean distance between u and v, α is an exponent depending on the environment [2], and t is the predetection threshold (in mW) at the receiver side, $t > 0$. The network can be represented as a digraph $G_{max}(V)$, where a directed edge $uv \in G_{max}(V)$ if and only if $td(u,v)^\alpha \le p_{max}(u)$. In addition, node v needs additional c power to receive from u. Therefore, the least power required for a transmission from u to v in this model is $c + td(u,v)^\alpha$ [7].

Generally speaking, the topology control is to determine a subgraph of $G_{max}(V)$. Consider a controlled topology $G(V)$. The *transmission radius* and *degree* of a node u in $G(V)$ are defined, respectively, as

$$T_u(G(V)) = max_{uv \in G(V)} d(u,v); \tag{1}$$

$$D_u(G(V)) = |\{v \in V | uv \in G(V)\}|. \tag{2}$$

Let $\pi(u,v) = v_0 v_1 \cdots v_{h-1} v_h$ denote a path connecting two nodes u and v, where $v_0 = u$ and $v_h = v$. The *total transmission power* required to relay on $\pi(u,v)$ is

$$P(\pi(u,v)) = \sum_{i=1}^{h} [c + td(v_{i-1}, v_i)^\alpha]. \tag{3}$$

In worse-case situations, the energy efficiency of nodes is measured by the *maximum node degree*, $D_{max}(G(V))$, and the energy efficiency of routes being preserved is measured by the *power stretch factor* [3]

$$\rho(G) = max_{uv \in V} \frac{P(\pi^*_{G(V)}(u,v))}{P(\pi^*_{G_{max}(V)}(u,v))},$$

where $\pi^*_{G(V)}(u,v)$ is the path with the least total transmission power between u and v in $G(V)$.

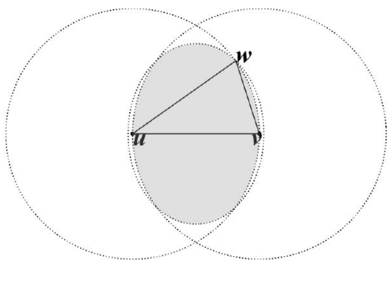

Fig. 2. The general r-neighborhood region of u and v.

3 Graphic Structures

In this section, we first generalize the r-neighborhood graph to a more realistic power consumption model and variant r_u's. Then, an equivalent structure is defined to facilitate the design of an energy-efficient maintenance protocol in the next section.

3.1 Generalization

First of all, we define the following region under the power consumption model $P(uv) = c + td(u, v)^\alpha$, for any two nodes u and v.

Definition 1. *Given two nodes u and v on* $\aleph$, *and* $0 \leq r \leq 1$, *the general r-neighborhood region of u and v is defined as*

$$NR_r^*(u, v) = \left\{ \begin{array}{l} x \in \aleph : d(u, x) < d(u, v), \\ d(v, x) < d(u, v), \\ P(uxv) < P(uv)(1 + r^\alpha) \end{array} \right\}.$$

Fig. 2 shows the general r-neighborhood region (the shaded regions) of two nodes u and v. Compared with Fig. 1, we can see that $NR_r(u, v)$ and $NR_r^*(u, v)$ are only diverse in their third conditions, which correspond to an inner circle and an inner ellipse, respectively. The condition indicates that the total power required by relaying through any node w in $NR_r^*(u, v)$ (i.e., $\pi(u, v) = uwv$) is not worse than $(1 + r^\alpha)$ times of a direct transmission from u to v.

Based on this region, the graph with variant r_u's is defined as follows.

Definition 2. *Given a set V of n nodes on* $\aleph$, *a set* $f_r : \{r_{v_1}, r_{v_2}, \ldots, r_{v_n}\}$, $0 \leq r_{v_i} \leq 1$, *the general* f_r*-neighborhood graph of V, denoted as* $NG_{f_r}^*(V)$, *has an edge uv if and only if* $uv \in G_{max}(V)$ *and there is no other node w such that* $Loc(w) \in NR_{r_{uv}}^*(u, v)$, *where* $r_{uv} = max\{r_u, r_v\}$.

A three-node example of $NG_{f_r}^*(V)$ is depicted in Fig. 3. The regions with respect to r_u, r_v, and $r_{v'}$ are filled with gray, twill, and white, respectively. We can see that the gray area determines edge uv' because $r_{v'} < r_u$, while edge uv is determined by the twilled area because $r_u < r_v$. That is, the presence of an edge is now determined by the larger one of the two sides, instead of an identical r.

Let $NG_{f_r|r_u=r_0}^*$ represent the case where the parameter of a node u is fixed on a ratio r_0. We have the following monotonic property with respect to each r_u (see Appendix F.1, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68 for the proof).

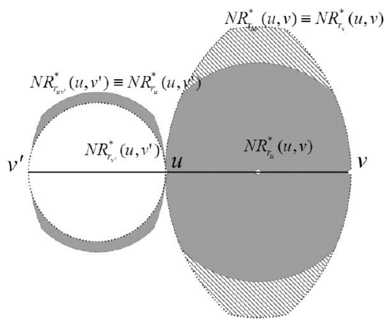

Fig. 3. General f_r-neighborhood graph of nodes v', u, and v, where $r_{v'} < r_u < r_v$.

Property 1. *Given a set V of n nodes on* $\aleph$, *for any* $f_r : \{r_{v_1}, r_{v_2}, \ldots, r_{v_n}\}$, *and* $0 \leq r_1 \leq r_2 \leq 1$,

1. $D_u(NG_{f_r|r_u=r_2}^*) \leq D_u(NG_{f_r|r_u=r_1}^*)$, $\forall u \in V$;
2. $T_u(NG_{f_r|r_u=r_2}^*) \leq T_u(NG_{f_r|r_u=r_1}^*)$, $\forall u \in V$;
3. $P(\pi_{NG_{f_r|r_u=r_1}^*}^*(s, t)) \leq P(\pi_{NG_{f_r|r_u=r_2}^*}^*(s, t))$, $\forall s, t \in V$.

We can see that no matter what the values of other parameters in f_r are taken, a node u can conserve its own energy by choosing a larger r_u, i.e., reducing its $D_u(NG_{f_r}^*(V))$ and $T_u(NG_{f_r}^*(V))$. On the contrary, if node u has sufficient energy, it can just choose a smaller r_u to support more energy-efficient routing, i.e., reducing $P(\pi_{NG_{f_r}^*(V)}^*(s, t))$, for any possible communication pair of s and t.

Let $NG_r^*(V)$ denote the case where $r_u = r$ for any $u \in V$. The worst-case performance for an identical r is presented below (proven in Appendix F.2, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68).

Property 2. *Given a set V of n nodes on* $\aleph$, *for any* $0 \leq r \leq 1$,

1. $D_{max}(NG_r^*(V)) \leq \lceil \pi / \sin^{-1}(r/2) \rceil$, *if* $c = 0$;
2. $\rho(NG_r^*(V)) \leq 1 + r^\alpha(n - 2)$.

Property 2(2) shows that the graph preserves the upper bound of the power stretch factor as proven in [8], even if it is now defined under a general power consumption model. On the other hand, the node degree's bound in [8] is also preserved in Property 2(1), but it is restricted to the case where the receiving cost is negligible, i.e., $c = 0$. However, the new structure can result in a much lower degree and shorter transmission radius for $c > 0$ in an average sense, especially when the path loss exponent α is large (see the numerical results in Appendix D.1, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68).

For the case of variant r_u's, the two upper bounds in Property 2 are clearly determined by the largest and smallest r_u's in f_r, denoted as r_{min} and r_{max}, respectively. Therefore, it is easy to infer that

$$D_{max}(NG_{f_r}^*(V)) \leq \lceil \pi / \sin^{-1}(r_{r_{min}}/2) \rceil, \text{if } c = 0,$$

and

$$\rho(NG_{f_r}^*(V)) \leq 1 + r_{max}^\alpha (n - 2).$$

Finally, the property below shows that our structure is symmetric and connected (the proof is in Appendix F.3, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68). A topology is symmetric if the presence of an edge implies that its inverse exists, which is important, since the designs of many network primitives, such as collision avoidance, would become very complicated if links are asymmetric. Moreover, connectivity is unquestionably the prerequisite in any network.

Property 3. *Given a set V of n nodes on $\aleph$, for any $f_r : \{r_{v_1}, r_{v_2}, \ldots, r_{v_n}\}$,*

1. *$NG^*_{f_r}(V)$ is symmetric;*
2. *$NG^*_{f_r}(V)$ is connected.*

The relationship between $NG_r(V)$ and $NG^*_{f_r}(V)$ is as follows (see Appendix F.4, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68, for the proof).

Property 4. *Given a set V of n nodes on $\aleph$, for any $0 \leq r \leq 1$, if $c = 0$, $\alpha = 2$, and $r_u = r$ for any $u \in V$,*

$$NG^*_{f_r}(V) \equiv NG_r(V).$$

We can see that the two structures are equivalent when $\alpha = 2$ and $c = 0$. In other words, $NG^*_{f_r}(V)$ is a general structure of $NG_r(V)$ in terms of α and c.

3.2 Equalization

Now, we present an equivalent structure of the general f_r-neighborhood graph, called the general *f_r-enclosed graph*. The basic idea is borrowed from the *enclosed graph*, proposed by Rodoplu and Meng [7].

First, we define a duality[1] of the general r-neighborhood region.

Definition 3. *Given two nodes u and w on $\aleph$, $0 \leq r \leq 1$, $\alpha \geq 2$, the general r-relaying region of u and w is defined by*

$$RR^*_r(u, w) = \left\{ \begin{array}{l} x \in \aleph : d(u, w) < d(u, x), \\ d(w, x) < d(u, x), \\ P(uwx) < P(ux)(1 + r^\alpha) \end{array} \right\}.$$

A region, enclosed by the complements of the general r-relaying regions, is given as follows.

Definition 4. *Given a set V of nodes on $\aleph$, the general r-enclosed region of a node u is defined by*

$$ER^*_r(u) = \bigcap_{uw \in G_{max}(V)} \{\aleph \cap R_{max}(u) - RR^*_r(u, w)\}.$$

Based on the region, the graph is defined below.

Definition 5. *Given a set V of n nodes on $\aleph$, a set $f_r : \{r_{v_1}, r_{v_2}, \ldots, r_{v_n}\}$, $0 \leq r_{v_i} \leq 1$, the general f_r-enclosed graph of V, denoted as $EG^*_{f_r}(V)$, has an edge uv if and only if $uv \in G_{max}(V)$ and $Loc(v) \in ER^*_{r_{uv}}(u)$, where $r_{uv} = \max\{r_u, r_v\}$.*

1. See Appendix B.1, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68, for two comparisons that explain the dual relationship between the two regions.

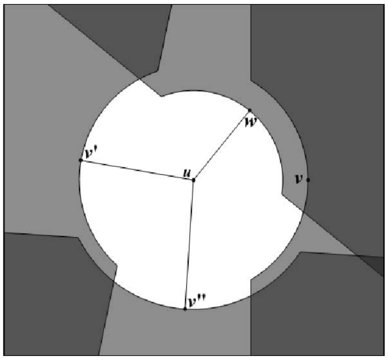

Fig. 4. General f_r-enclosed graph of a node u, where $c = 0$, $\alpha = 2$, and r_u, r_v, $r_{v'}$, $r_{v''}$ are all set as 1.

Fig. 4 shows the f_r-enclosed region of a node u (white area), which is enclosed by the four r-relaying regions (dark areas) of u with surrounding nodes v, v', v'', and w (the darker areas are overlapped by two or more regions). We can see that a node has a link from u if and only if it is located in the f_r-enclosed region of u. To see how r_u changes the shapes of our defined regions, readers can refer to Appendix B.2, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68, for further illustration.

Now we show that the two structures are equivalent (See Appendix F.5, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68, for the proof).

Property 5. *Given a set V of n nodes on $\aleph$, for any $f_r : \{r_{v_1}, r_{v_2}, \ldots, r_{v_n}\}$, $0 \leq r_{v_i} \leq 1$,*

$$NG^*_{f_r}(V) \equiv EG^*_{f_r}(V).$$

4 Energy-Efficient Maintenance

Based on the equivalence in Property 5, in this section, we design an energy-efficient maintenance protocol for the general f_r-enclosed graph.

4.1 The ANGTC Protocol

The main idea of this protocol is to utilize the information partially received from nearby nodes to confine the broadcasting radiuses of subsequent beacons.

In every time interval of Δ, each node broadcasts a beacon at a certain radius to nearby nodes. Consider a node u. Let S_u denote the set of nodes detected by u during the previous Δ time. Similar to Definition 4, we define $ER^*_r(u|S_u)$ as the general r-enclosed region of u based on nodes in S_u, i.e.,

$$ER^*_r(u|S_u) = \bigcap_{w \in S_u} \{\aleph \cap R_{max}(u) - RR^*_r(w, v)\}. \qquad (4)$$

The set of nodes in S_u being enclosed by node u in $EG^*_{f_r}(V)$ is specified as

$$N_u = \{v \in S_u | Loc(v) \in ER^*_{r_{uv}}(u|S_u)\}. \qquad (5)$$

In addition, we denote λ_u as the least radius covering $ER^*_{r_u}(u|S_u)$, i.e.,

$$\lambda_u = \max\{d(u,x)|x \in ER^*_{r_u}(u|S_u)\}. \quad (6)$$

With the definition in (6), for any node v in S_u, if u is within the radius λ_v of v which covers $ER^*_r(v|S_v)$, then v will be included in a nodes set B_u. This is,

$$B_u = max\{v \in S_u | d(u,v) < \lambda_v\}. \quad (7)$$

The radius covering all nodes in B_u is specified by

$$\chi_u = max\{d(u,v)|v \in B_u\}. \quad (8)$$

Then, in the next maintenance process, node u will broadcast its current position $Loc(u)$, λ_u, and r_u using the beacon to nearby nodes at the radius M_u, where

$$M_u = max\{\lambda_u, \chi_u\}. \quad (9)$$

On the other hand, if node u cannot receive the beacon from a node v over a beacon interval Δ, the information about v will be discarded. In other words, for every maintenance process, the broadcasting radius M_u of u is adjusted to cover both the area in $ER^*_r(S_u)$ and all nodes in B_u, depending on the information received during the previous Δ interval. For every Δ time, the value of r_u will be reconfigured and broadcasted to nearby nodes along with the periodic beacon message. The protocol, named ANGTC, is now presented below.

ANGTC PROTOCOL

$N_u = \{\}$; $S_u = \{\}$; $B_u = \{\}$;
For every Δ time
  reconfigure r_u;
  $N_u = \{v \in S_u | Loc(v) \in ER^*_{r_{uv}}(u|S_u)\}$;
  $\lambda_u = \max\{d(u,x)|x \in ER^*_{r_u}(u|S_u)\}$;
  $\chi_u = \max\{d(u,v)|v \in B_u\}$;
  $M_u = \max\{\lambda_u, \chi_u\}$;
  Broadcast ($Loc(u)$, λ_u, r_u) at the radius M_u;
Upon receiving ($Loc(v)$, λ_v, r_u) from a node v,
  $S_u = S_u + \{v\}$;
  If $d(u,v) < \lambda_v$, $B_u = B_u + \{v\}$;
Upon not receiving from v over Δ time,
  $S_u = S_u - \{v\}$; $B_u = B_u - \{v\}$.

An example of the ANGTC protocol is elaborately illustrated in Appendix C, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68.

4.2 Correctness and Convergency

Now, we discuss the correctness and convergency of the ANGTC protocol. We show that after nodes' placement changes, the neighbor set N_u and maintenance radius M_u of each node u can be correctly recalculated and converged to a stable status in constant time.

We assume that the propagation delay and computation time are relatively small in comparison with Δ and the starting points of every time interval among nodes are aligned (i.e., a synchronous network). Without loss of generality, we consider the case of $\Delta = 1$ henceforth. In addition, we assume that the configuration of each r_u is temporarily fixed before the radius M_u is converged. Let X^t stand for the status of a variable X at time t, and $N_u(G)$ denote the neighbor set of a node u in a graph G. The results are shown in the following property (proven in Appendix F.6, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68).

Property 6. *Given a set V of nodes on $\aleph$, a placement change occurs during $[t-1, t]$, i.e., $\exists u \in V$, $Loc^{t-1}(u) \neq Loc^t(u)$, and there is no further change after t, i.e., $\forall u \in V$, $k > 0$, $Loc^t(u) = Loc^{t+k}(u)$. If the network is synchronous, and the parameter r_u of each $u \in V$ is fixed after time t,*

1. *$N_u(EG^*_{f_r}(V)) \subseteq N_u^{t+2}$;*
2. *$N_u(EG^*_{f_r}(V)) = N_u^{t+k}$, for any $k \geq 3$;*
3. *$M_u^{t+4} = M_u^{t+k}$, for any $k > 4$.*

Property 6(1) indicates that the ANGTC protocol can find out all links in $EG^*_{f_r}(V)$ in 3Δ after a change occurs. Besides, Properties 6(2) and (3) show that the correct neighbor set N_u and maintenance radius M_u converge in 4Δ and 5Δ, respectively. The convergency of M_u is important, because the continuing change in broadcast radius will incur additional energy expense and latency for power switching.

For an asynchronous network, after the change during $[t-1, t]$, each node u can receive updated positions from nearby nodes before $t+2$. Hence, the converged time is postponed by at most Δ, i.e., 5Δ and 6Δ for N_u and M_u, respectively.

About the communication cost, as shown in Property 3(1), since our graph is inherently symmetric, nodes are not required to exchange their neighbor lists. Thus, each message has only constant bits.

4.3 Further Power Shrinking

Although the ANGTC can reduce the beacon power, the radius M_u could be too large to cover some nodes which are not essential for the operations. Therefore, we attempt to further shrink the radius.

Consider two nodes u and v. Let $ER^*_{r_v}(v|B_u)$ denote the enclosed region of v based on nodes in B_u, i.e.,

$$ER^*_r(v|B_u) = \bigcap_{w \in B_u} \{\aleph \cap R_{max}(u) - RR^*_r(v,w)\}.$$

We define

$$B'_u = \{v \in B_u | ER^*_{r_{uv}}(v|B_u) \neq ER^*_{r_{uv}}(v|B_u + \{u\})\},$$

and

$$\chi'_u = max\{d(u,v)|v \in B'_u\}.$$

Because B'_u is a subset of B_u, χ'_u must be smaller than (or at most equal to) χ_u.

Below, we show that Property 6 is still preserved when χ_u is replaced by χ'_u in the ANGTC. Since the definition of λ_u is not changed, it is sufficient to prove the property below (see Appendix F.7, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68, for the proof).

Property 7. *Given a set V of nodes on $\aleph$, for any $u \in V$ and $w \in S_u^*$, $u \in B'_w$.*

We have also conducted a numeric study for our protocol. The results show that the ANGTC can significantly reduce the average transmission radius by 5 to 60 percent. The power shrinking mechanism can further shrink the radius up to 10 percent. The detailed results can be found in Appendix D.2, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68.

5 Adaptive Configuration Rule

In this section, we propose an adaptive configuration rule for the ANGTC protocol. We first analyze how an individual r_u affects the overall energy efficiency from the following three points.

1. *Energy efficiency of nodes versus Energy efficiency of routes*. No matter what the values of other parameters in f_r are, Property 1 has shown that a smaller r_u can always lead to an overall improvement in the energy efficiency of routes, and a node u can conserve its own energy by simply turning up its r_u.
2. *High mobility versus Low mobility*. If a node moves frequently, its links are unstable, which in turn costs more energy for route reconstruction, and deteriorates the quality of the established routes. In this case, the node should keep a lower degree to reduce its dependency on nearby nodes by turning up its r_u. On the contrary, if a node has lower mobility, it should turn down its r_u to construct more reliable routes.
3. *Topology maintenance power*. In the ANGTC protocol, the broadcasting radius M_u is not fixed. As shown in Property 8 (proven in Appendix F.8, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68), it could be varied by the configuration of r_u.

Property 8. *In the ANGTC protocol, for each node u, the broadcasting radius M_u is decreased by r_u.*

Concluding the above observations, we have two principles for adjusting r_u:

1. If a node u has sufficient energy or rarely moves, it should connect with more neighbors to improve the energy efficiency as well as the stability of routes. In this case, a smaller r_u is preferred.
2. If a node has insufficient energy or moves frequently, a smaller r_u that leads to a lower node degree, transmission radius, and beacon power is desired.

Accordingly, the adaptive configuration rule is characterized as follows:

$$r_u = \left(1 - \frac{Energy_u}{Energy_{Full}}\right) w_{e,u} + \left(\frac{Mobility_u}{Mobility_{Max}}\right) w_{s,u}, \qquad (10)$$

where $Energy_u$ and $Mobility_u$ stand for the residual energy and current mobility of node u, and $Energy_{Full}$ and $Mobility_{Max}$ represent the full energy level and the maximum mobility level, respectively. In addition, we adjust the impact from residual energy and mobility level by two weights $w_{e,u} = 1 - (Energy_u/Energy_{Full})$ and $w_{s,u} = 1 - w_{e,u}$. At the initial stage, since nodes have little deviation in their residual energy (assuming the initial energy is equal), the mobility dominates the value of r_u. As time goes by, the impact from node's energy will become more and more significant.

6 Experiments

In this section, we compare the ANGTC with existing topology control protocols for mobile nodes using the ns2 simulator [8]. For each test case, we simulated 50 networks, each with 100 nodes uniformly placed on a 1,000 meters square region. Each node has a maximum transmission radius of 500 meters and is initiated by 0.5 Joules. The 802.11b MAC is used for link-layer contention. We modify the DSDV routing protocol [9] such that packets are conveyed on the least-energy path. The connections of CBR traffic are established for 20 distinct source-destination pairs, and the packet size is 256 bytes. The energy cost consists of all network operations during the simulation. The mobility pattern is based on the random-way point model. We test three speed intervals of [0, 5], [0, 15], and [0, 30] m/s, to imitate *low-speed*, *middle-speed*, and *high-speed* circumstances, respectively. In addition, the pause time of each node is randomly taken from [0, 5] s. Each run lasts 200 s.

For comparison, we also implemented the following protocols in the ns2: the SMECM [10] is considered appropriate for conserving route energy. It preserves the least-energy path (i.e., $\rho = 1$) for any node pair. On the other hand, the XTC [11] is considered appropriate for conserving nodes' energy. It confines node degrees to within 6, with connectivity guaranteed. The K-NEIGH [12] is considered resilient to node mobility. It only requires nodes to identify their K-closest neighbors instead of their precise positions. A pruning stage is proposed in [12] to revoke redundant links. We denote this version as K-NEIGH*. Here, we take $K = 9$, which is the least value for the topology to be connected with a probability of 0.95 [12]. For more details, readers can refer to Appendix E, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.68, where we provide a review of related protocols.

Figs. 5a and 5b report the power ratio and average transmission radius for stationary nodes. The power ratio, defined as

$$\frac{\sum_{u,v \in V} p(\pi_G^*(u,v))}{\sum_{u,v \in V} p(\pi_{G_{max}}^*(u,v))},$$

measures the average energy efficiency of the routes. We can see that the SMECN always preserves the optimal routes, but it compensates for a larger transmission radius. On the other hand, the power ratio of the XTC is about six percent larger than the optimal, but it has a much smaller transmission radius. The radius of K-NEIGH can be reduced significantly in the pruning stage, but it is still

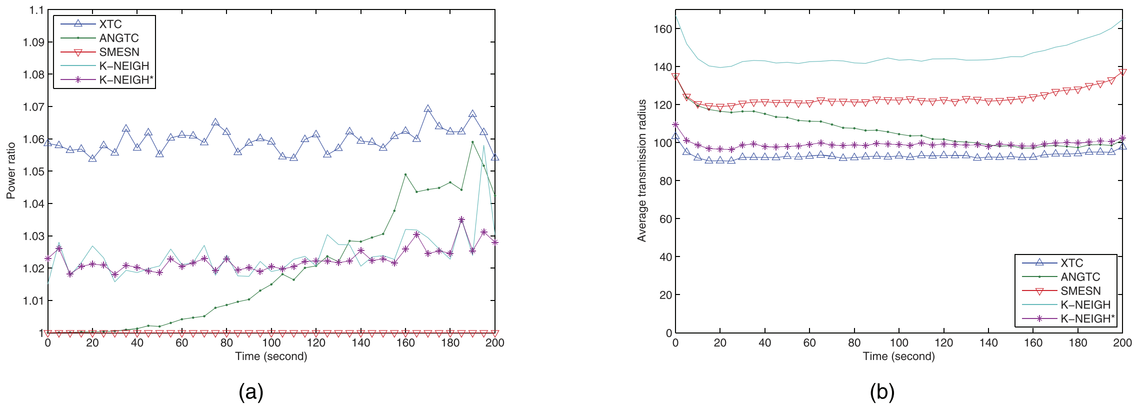

Fig. 5. (a) Energy efficiency of routes. (b) Energy efficiency of nodes.

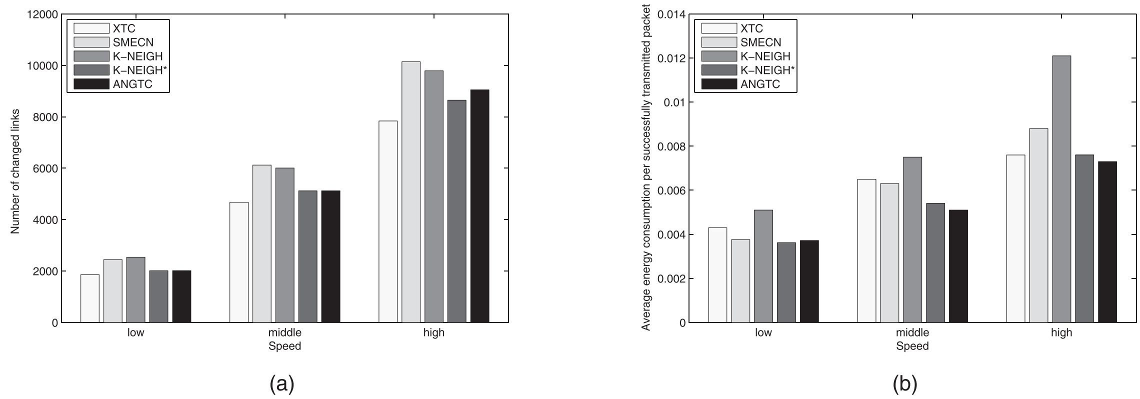

Fig. 6. (a) Number of changed links. (b) Overall energy efficiency of communication.

slightly above than that of the XTC. However, these protocols have no flexibility as the energy level goes down with time. In contrast, the ANGTC allows nodes to adjust their ways of conserving energy. At the beginning, since each node u has full energy, according to (10), the parameter r_u is close to 0, which forces node u to support energy-efficient routing. As time goes by, r_u is gradually raised to 1 so that node u can reduce the radius to conserve its own energy.

Fig. 6a shows the number of changed links. It measures the stability of a topology under nodes' mobility. The XTC has the least link changes, since each node only has to maintain no more than six links. The K-NEIGH* also performs well, because keeping the order of nodes is much easier than keeping the precise positions. Although the ANGTC uses positions and has more links than XTC, the stability is nearly at the same level for both of them. The reason is that our configuration rule can adaptively reduce to the degree of a node if the node moves frequently.

Fig. 6b reports the average energy consumption per successfully transmitted packet. It measures the overall energy consumption for a communication, including routing, route reconstruction, and retransmissions. In low-speed networks, since links change rarely, the energy efficiency of routes is relatively important. In this case, the SMECN is suitable. On the contrary, the XTC performs well in high-speed networks, because a large portion of energy may be consumed for advertising the link's changes. Since the ANGTC can change link status according to node mobility, it accommodates well in both cases. Our protocol, however, can perform even better. One possible reason is that the K-NEIGH* (and K-NEIGH) is only connected in a probability sense, while the general f_r-neighborhood graph always guarantees connectivity. Hence, our protocol requires less energy for retransmissions before a packet arrives successfully.

The number of living nodes with middle speed is drawn in Fig. 7 (the results are almost the same for the other two speeds). Even though the transmission radius and node degree of the ANGTC are not lowest, it still outperforms the others. This is because the enhancement of routes can also reduce the energy expenditure of nodes. In other words, the nodes' energy synergically is conserved in these two ways.

Fig. 8 shows the ratio of the maintenance radius (power) to the maximum transmission radius (power) The results show that our protocol requires no more than 50 percent of power to maintain the topology. With this improvement, the power can be further reduced by over 20 percent. Notice that the radius (power) steadily decreases along with the depletion of node energy and slightly increases when some nodes are exhausted.

7 Conclusions

In this paper, we have generalized the r-neighborhood graph into a more realistic power consumption model with independent parameter r_u to each node u. For mobile nodes, we have also proposed an energy-efficient maintenance protocol to reduce the beacon power. It has been proven

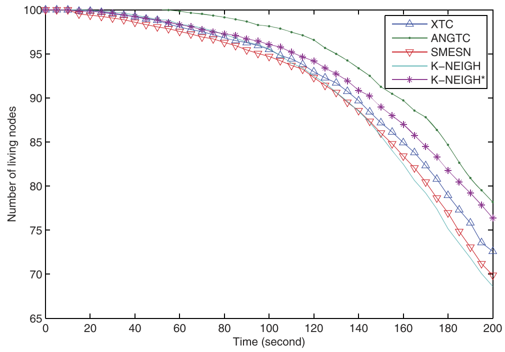

Fig. 7. Number of living nodes.

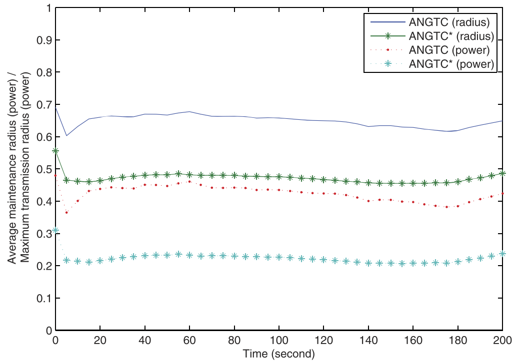

Fig. 8. Maintenance radius and power.

that any reconstruction and power change can coverage in four and five beacon intervals. Finally, an adaptive configuration rule is given to configure the parameter for each node based on the node's mobility and energy levels. Experimental results show that our protocol has significantly reduced the overall energy consumption and network lifetime. For future research, a node may lose important information to construct the graph if a collision occurs. It is, thus, worthwhile to design a collision avoidance mechanism for the ANGTC protocol.

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Andy An-Kai Jeng received the BS degree in statistics from Tamkang University, Taiwan, in 2001, the MS degree in management information systems from the National Chi Nan University, Taiwan, in 2003, and the PhD degree in the computer science from National Chiao Tung University, Taiwan, in 2007, where he is currently a postdoctoral researcher. His research interests include wireless networks, distributed algorithm design and analysis, scheduling theory, and operations research.

Rong-Hong Jan received the BS and MS degrees in industrial engineering and the PhD degree in computer science from the National Tsing Hua University, Taiwan, in 1979, 1983, and 1987, respectively. From 1991-1992, he was a visiting associate professor in the Department of Computer Science, University of Maryland, College Park. He joined the Department of Computer and Information Science, National Chiao Tung University, in 1987, where he is currently a professor. His research interests include wireless networks, mobile computing, distributed systems, network reliability, and operations research. He is a senior member of the IEEE Computer Society.