Optimizing Energy Consumption of Data Flow in Mobile Ad Hoc Wireless Networks[1]

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Abstract: Because of the limited node battery power, energy optimization is important for the mobile nodes in wireless ad hoc networks. Controlled node mobility is an effective approach to reduce the communication energy consumption while the movement itself also consumes energy. Based on cooperative communication (CC) model, this paper takes the energy consumption of node movement and their individual residual energy into account, and then proposes localized algorithms for directing mobile node mobility and adapting their transmission power dynamically in mobile ad hoc networks. Compared with other algorithms by simulation, our mechanism named DEEF shows its efficiency in improving the system lifetime.

Key-Words: ad hoc networks; node mobility; cooperative communication; energy consumption; multi-flow; local algorithm

1 Introduction

Ad hoc wireless networks consist of multiple wireless nodes that can communicate with each other by sending data flows either directly or through intermediate relays in the absence of a fixed infrastructure. The network topology, and specifically, the paths of flows, significantly affects communication energy efficiency at individual nodes. Being battery powered, these wireless nodes have limited operational time. Disproportionate energy consumption among them can lead to failure of the network. Recently, the optimization of the energy utilization of wireless nodes has received significant attention [9], [20], [21]. Different energy optimi-zation techniques including clustering [1], node mobility[12] and topology control [2], [3], [4] have been proposed.

In this paper, we use the approach of controlled node mobility to reduce the energy consumption of data flows in the mobile ad hoc network. We also take advantage of cooperative communication (CC) models to direct the nodes' movement. By an effective incorporation of the node mobility and CC model, we present a distributed energy-efficient flow scheme named DEEF to support data transmission in flow paths with less transmission power, and each mobile node are enable to make local decision on their controlled mobility.

The remainder of this paper is organized as follows: In Section 2, we overview the related works. Section 3 describes the energy model and CC model. Problem description is also given in this section. In section 4, we analyze the controlled mobility optimization problem under CC model and discuss DEEF in detail that make controlled mobility decisions at individual nodes to maximize the system life. Section 5 presents the simulation results for DEEF and other algorithms, and section 6 concludes this paper.

2. Related Works

In ad hoc wireless networks, mobile nodes can optimize their energy management by the approach of mobility. With predicting node movement, this kind of strategy has been used for topology control

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[6], energy optimization [7], and network throughput improvement [8]. In these approaches, the mobile nodes change their locations to optimize their transmission power and reducing energy consumption at other nodes. This controlled mobility strategy has been used widely as a means to reduce total energy consumption [10], [14], [15], [22], recover a disconnected topology [9], and increase sensor surveillance coverage [11], [12].

There are a lot of works discussing this controlled mobility. In [9], the authors proposed an approach that uses controlled mobility to improve communication reliability, specifically, to reconnect a partitioned mobile ad hoc network. In [11], [12], the authors presented localized algorithms that increase sensor surveillance coverage by distributing mobile sensor nodes to new locations where there were no other sensor nodes. In addition to the above research, other research activities on controlled mobility in sensor networks are reported in [18].

In [5], the authors consider energy consumption for both communication and mobility, then present global algorithm and localized algorithm to maximize the lifetime of flow and minimize the energy consumption. They incorporate the cost-benefit trade-off in the design of mobility strategies to optimize energy consumption.

In [10], the authors proposed several approaches that adjust the network topology to reduce energy consumption for the application of data flow. The approaches are based on the observation that total energy consumption is minimized when all relaying nodes are evenly spaced on a straight line between the source and the destination.

In [2], the authors address the topology control with cooperative communication (CC) problem in ad hoc wireless network. The model allows combining partial messages to decode a complete message. The objective of the [2] is to obtain a strongly-connected topology with minimum total energy consumption. Two distributed and localized algorithms are presented in [2] to be used by the nodes to set up their transmission power. Both algorithms can be applied on top of any symmetric, strongly-connected topology to reduce total power consumption.

Based on the above works, to optimize nodes' energy consumption and maximize the lifetime of the system, this paper present a new localized mechanism named DEEF for data transmission in mobile ad hoc networks. It uses CC model among the mobile nodes, take the energy consumption of nodes' mobility and their residual energy into account, and then proposes localized algorithms to direct mobile node mobility and adapt their transmission power dynamically. Compared with other algorithms, our work shows its efficiency.

3. Problem Formulation

In this section, we introduce the energy models for wireless communication, and CC model in this paper. Problem description is also given in this section.

3.1 Energy Models

We adopt a transmission power model similar to the one used in [10] and [5]. In this model, the power for successful wireless data transmission is determined by the distance among the nodes and the noise level of their communication channel. Let $P(d)$ be the power needed for data transmission across distance *d*, then

$$P(d) = a + bd^{\alpha} \tag{1}$$

Here, *a*, *b*, and α are constants dependent on the characteristics of the communication channel. The value of α is usually greater than or equal to 2. The energy consumption for transmitting *l* data bits across distance d is

$$E_{Tra}(d) = l \cdot P(d) \tag{2}$$

In addition to transmission energy consumption, we also consider the energy consumption for node mobility. Of course, mobility cost is dependent on the actual trace of node movement. For simplicity, we adopt a distance proportional cost model similar to the one used in [10]. In this model, the mobility cost $E_{Mob}(d)$ can be calculated from the distance traversed,

$$E_{Mob}(d) = k_m d \tag{3}$$

Here, k_m is a constant dependent on the environment and the mass of the mobile node. For simplicity, we don't take mobile node's energy consumption for receiving data into account.

3.2 Cooperative Communication Model

In this paper, we take advantage of cooperative communication (CC) models that allows combining partial signals containing the same information to obtain the complete data. The CC model, has been introduced in [2], [11], and [19], in which transmitting independent copies of the signal from different locations results in having the receiver obtain independently faded versions of the signal, thus reducing the fading effect through multi-path propagation. In this communication model, each wireless node is assumed to transmit data and to act as a cooperative role, relaying data from other users. There are three versions of CC techniques [11] as amplify-and-forward, decode-and-forward, and selection relaying. This paper use the decode-and-forward version, where a node makes the relaying decision based on the signal-to-noise ratio (SNR) of the signal received. This model takes advantage of the physical layer design that combines partial signals containing the same information to obtain complete information.

The same to [2], [19], in this paper the message transmitted between nodes is encapsulated into a packet, which contains a preamble, a header, and a payload. A preamble is a sequence of predefined uncoded symbols assigned to facilitate timing acquisition, a header contains the error-control coded information sequence about the source/destination address and other control flags, and a payload contains the error-control coded message sequence.

There are two parameters related with SNR: θ_p and $\theta_{\alpha cq}$. θ_p denotes the threshold needed to successfully decode the packet payload, and $\theta_{\alpha cq}$ denotes the threshold required for a successful time acquisition. We use k to denote the ratio of these two thresholds, $k = \theta_{acq} / \theta_p$. We assume that the threshold to successfully decode a header is less than or equal to the threshold to successful time acquisition. A packet received with a SNR θ is: 1) fully received, if $\theta_p \le \theta$, 2) partially received, if $\theta_{acq} \le \theta \le \theta_p$, and 3) unsuccessfully received, if $\theta < \theta_{acq}$. Therefore, when a packet is fully or partially received ($\theta_{acq} \le \theta$), the header information is successfully decoded. In this paper, without losing generality, we only consider the case when $\theta_p = 1$, thus $k = \theta_{acq} / \theta_p = \theta_{acq}$.

In the Ad hoc network using CC model, if node i has set its transmission power level $pow_i = a + br_i^{\alpha}$, where α is a communication medium dependent parameter, r_i is the communication range of node *i*. And d_{ij} is denoted as the Euclidean distance between the nodes *i* and *j*, then the coverage provided by node *i* to node *j* is defined as: 1) cov_{ij} = 1, if $pow_i / (a + bd_{ij}^{\alpha}) \ge 1$; 2) cov_{ij} = $pow_i / (a + bd_{ij}^{\alpha})$, if $\theta_{acq} \le pow_i / (a + bd_{ij}^{\alpha}) < 1$; 3) cov_{ij} = 0, if $pow_i / d_{ij}^{\alpha} < \theta_{acq}$. In CC model, the fully received packet is defined as follows: suppose node *j* has *m* different neighbours; now, considering a transmission from node *i* to node *j*, if $\theta_{acq} \le pow_i / (a + bd_{ij}^{\alpha}) < 1$, then node *j* is partially covered by *i* (or fully covered by *i*, if $pow_i / (a + bd_{ij}^{\alpha}) \ge 1$). If combining all the packets partially or fully received from the different neighbors results in a full coverage of node *j*, i.e. $\sum_m pow_m / (a + bd_{mj}^{\alpha}) \ge 1$, then for node *j*, the packet is fully received.

3.3 Problem Description

We assume in ad hoc wireless network, the nodes are equipped with omni-directional antennas, and they are capable of receiving and combining partial received packets in accordance with the CC model.

For a flow composed of multiple nodes, we assume that the source and destination nodes of it are stationary, and other nodes are free to move to their new locations. The assumptions about energy consumption are made as follows:

- Nodes are energy constrained with battery-driven, and they are mobile except the source and destination nodes of a flow.
- Node movement consumes its energy.
- Nodes' transmission power are tunable. They can select a transmission power level close to a specified value and use this power level for transmission.
- Nodes can measure their residual node energy and detect their locations equipped with GPS or other position devices
- Nodes can move to location specified by software applications and protocols.
- Nodes can measure (or estimate from historical data) the energy needed to move to a target location, and they can determine the minimum transmission power needed to communicate with nodes within a specific distance.

4. Informed Mobility Using Cooperative Communication

This paper presents an adaptive mechanism named DEEF based on node mobility and CC model in wireless ad hoc networks to maximize the system lifetime. In our approach, the flow node disseminates mobility strategy and status to other nodes along the flow path using message header of data packets. This scheme ensures that the mobility is naturally synchronized without additional synchronization overhead. Under the idea of CC, mobile nodes exchange information of their residual energy and current locations with their neighbours on the flow path to decide their next optimal physical positions. We begin with a case where a data flow contains only three fixed nodes, and then present solutions for flows with multiple nodes.

4.1 Solution For Single-Flow with Fixed Nodes Under CC Model

Assume there is a one-to-one flow containing only three fixed nodes A, B and C in sequence, with their current locations (x_A, y_A) , (x_B, y_B) and (x_C, y_C) , and their residual energy e_A , e_B and e_C , respectively. d_{ij} denote the Euclidean distance between nodes *i* and *j*. In this physical area, $\theta_p = 1$, $k = \theta_{acq} / \theta_p = \theta_{acq}$ and $d_{AC} > d_{AB}$. Each node *i* has set its current transmission power as pow_i and $pow_i / (a + bd_{ij}^{\alpha}) \geq 1$. The energy consumed for nodes receiving data is ignored. Then, to prolong the life of the flow, each node will decide how to decrease or increase its transmission power and maintain data transmitting successfully along the flow at the same time. Let L_f denote the life of this flow. Clearly, L_f = *min* (e_A / pow_A , e_B / pow_B). A scheme under CC model is presented as follows to show how to maximize L_f by calculating A and B's new transmission power pow_A' and pow_B' respectively.

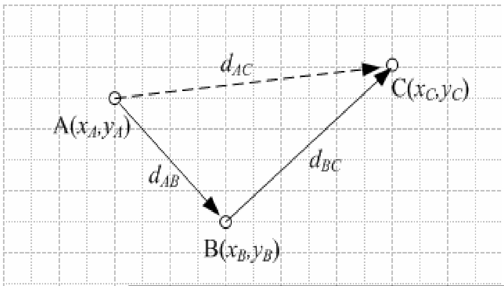

Figure 1 A flow containing three nodes *A*, *B* and *C*

If $e_A / pow_A > e_B / pow_B$, then $L_f = e_B / pow_B$. In this case, under CC model, node A's transmission power should be increased, so that node B can decrease its transmission power and node C may receive a part of data from node A directly. Node A will decide how to change its transmission power pow_A' between the domain $a + bd_{AB}^{\alpha} \leq$ pow_A' $\leq$ $a + bd_{AC}^{\alpha}$ (here, if pow_A' $\geq$ $a + bd_{AC}^{\alpha}$, node C will receive all the data from node A directly.). Next, the case are analyzed further by comparing $\frac{pow_A'}{a + b_{AC}^{\alpha}}$ with θ_{acq} . If $\frac{pow_A'}{a + b_{AC}^{\alpha}} < \theta_{acq}$, then node C can't receive any data from A, and node B has to set its new transmission power as pow_B' = $a + bd_{BC}^{\alpha}$. If $\frac{pow_A'}{a + b_{AC}^{\alpha}}$ $\geq$ θ_{acq} , then node C can receive some data from A, and node B will set pow_B' = *max*($\theta_{acq}(a + bd_{BC}^{\alpha})$, $(1 - \frac{pow_A'}{a + bd_{AC}^{\alpha}})(a + bd_{BC}^{\alpha})$) to satisfy the two conditions $\frac{pow_B'}{a + bd_{BC}^{\alpha}}$ $\geq \theta_{acq}$ and $\frac{pow_B'}{a + bd_{BC}^{\alpha}} + \frac{pow_A'}{a + bd_{AC}^{\alpha}} = 1$ simultaneously.

Following this analysis, let r_A denote node A's new transmission range, and r_B denote node B's new transmission range. We present the formula (4) to maximize the value of L_f .

$$\text{Max } L_f = \min(e_A / pow_A', e_B / pow_B');$$

$$\begin{cases} d_{AB} \leq r_A \leq d_{AC} \\ pow_A' = a + br_A^{\alpha} \\ r_B = d_{BC}, if\,(\frac{pow_A'}{a + bd_{AC}^{\alpha}} < \theta_{acq}) \\ r_B = \max((\frac{\theta_{acq}(a + bd_{BC}^{\alpha}) - a}{b})^{\frac{1}{\alpha}}, (((1 - \frac{pow_A'}{a + bd_{AC}^{\alpha}})(a + bd_{BC}^{\alpha}) - a)/b)^{\frac{1}{\alpha}}), if\,(\frac{pow_A'}{a + bd_{AC}^{\alpha}} > \theta_{acq}) \\ pow_B' = a + br_B^{\alpha} \\ e_A / pow_A' \geq e_B / pow_B' \\ e_B / pow_B' \geq e_B / pow_B \end{cases} \qquad (4)$$

For the case $e_A / pow_A < e_B / pow_B$, node A can't increase its power to partly cover C and it will set $pow_A' = a + bd_{AB}^{\alpha}$. Also, if $\frac{pow_A'}{a + b_{AC}^{\alpha}} < \theta_{acq}$, node B has to set its new transmission power as $pow_B' = a + bd_{BC}^{\alpha}$.

If $\frac{pow_A'}{a+b_{AC}^{\alpha}} \geq \theta_{acq}$, node B will set $pow_B' =$ $max(\theta_{acq}(a+bd_{BC}^{\alpha})$, $(1-\frac{pow_A'}{a+bd_{AC}^{\alpha}})(a+bd_{BC}^{\alpha}))$ to satisfy the two conditions $\frac{pow_B'}{a+bd_{BC}^{\alpha}} \geq \theta_{acq}$ and $\frac{pow_B'}{a+bd_{BC}^{\alpha}} + \frac{pow_A'}{a+bd_{AC}^{\alpha}} \geq 1$. Following this analysis, we present the formula (5) to maximize the value of L_f

$$\text{Max } L_f = \min(e_A / pow_A', e_B / pow_B');$$

$$\begin{cases} r_A = d_{AB} \\ pow_A' = a + br_A^{\alpha} \\ r_B = d_{BC}, if \left(\frac{pow_A'}{a+bd_{AC}^{\alpha}} < \theta_{acq}\right) \\ r_B = \max\left(\left(\frac{\theta_{acq}(a+bd_{BC}^{\alpha}) - a}{b}\right)^{\frac{1}{\alpha}}, \left(\left(\left(1-\frac{pow_A'}{a+bd_{AC}^{\alpha}}\right)(a+bd_{BC}^{\alpha}) - a\right)/b\right)^{\frac{1}{\alpha}}\right), if \left(\frac{pow_A'}{a+bd_{AC}^{\alpha}} > \theta_{acq}\right) \\ pow_B' = a + br_B^{\alpha} \end{cases} \quad (5)$$

As in real mobile ad hoc networks, global information is not always available at each node. For a flow containing multiple fixed nodes, we present a localized algorithm for it. In the algorithm, current node exchanges information of its residual energy only with its neighbors on the flow, and then constantly adjusts its transmission power according to their residual energy and their positions on the flow. The algorithm is presented in figure 3.

4.2 Solution for Multi-Flow with Fixed Nodes

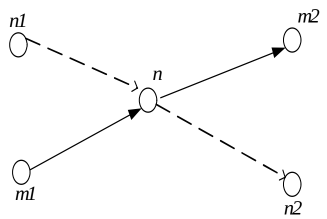

Figure 2 Scenario of multi-flow with fixed nodes

In real scenarios, a network may consist of multiple flows. In this ad hoc network with multiple flows, some relay nodes will be on the routing paths of multiple flows. As shown in figure 2, node *n* is such a relay node, which is on two different flows shown as the dashed arrow line, and the real arrow line. We propose another localized algorithm (see in figure 6) to deal with this scenario. In this algorithm, when a node *i* sends data to node *n* along the flow they are both on, node *n* will adjust its transmission power and tell *i* how to change its transmission power according to the CC model, their residual energy, and the distance between them. In this way, node *n* has to change its transmission power frequently to transmit data received along different flows.

4.3 Solutions for Single Flow with Mobile Nodes

In this section, a localized algorithm for single flow with mobile nodes is presented, whose basic idea is to have each node constantly adjust its position by exchanging the information of the positions and residual energy only with its neighbours. In the algorithm, node *i* takes mobility cost into consideration by periodically calculating the mobility benefit and the mobility cost, based on its current position and the next optimal position it will move to. Then, it decides whether to spend the energy on moving to its optimal position. Here, we use the theorem presented in [6], [13] to calculate the node's next optimal position according to its residual energy and positions. In the theorem, the optimal positions of all *N* nodes in a one-to-one flow must lie entirely on the straight line between the source node n_0 and the destination node n_{N-1}. Let e_i denotes the residual energy of node n_i (the *i*th node in the flow). Then, for any $0 \leq i \leq N-1$, $0 \leq j \leq N-1$, $pow_i(d_i)/pow_j(d_j) = e_i / e_j$, where d_i = distance (n_i, n_{i+1}), d_j = distance (n_j, n_{j+1}). As in real scenario, the global information is not always available for every node in the flow. Thus, an approximate local mechanism are presented in which a node decides its next optimal position at some point of the straight line between its neighbors according to their residual energy and positions. The algorithm is seen in figure 7.

In this paper, we also take network topology constraint of connectivity into account. In our DEEF mechanism, mobile nodes move under the constraint that during the movement it should not move outside of the transmission range of any of its current neighbours.

Alogorithm SingleFlowWithFixedNodes (Flow *f*)

For node n_i on the flow{

n_{i+1} is n_i 's next neighbor on the flow; n_{i+2} is n_{i+1} 's next neighbor on the flow;

Let $d_{i,i+1}$ be the Euclidean distance between n_i and n_{i+1};

Let e_i denote n_i 's current residual energy;

r_i denotes n_i 's new power range,

Then, n_i computes as the following process:

if($e_i /(a+bd^{\alpha}_{i,i+1}) > e_{i+1} /(a+bd^{\alpha}_{i+1,i+2}))$

for $d_{i,i+1} \le r_i \le d_{i,i+2}$ {

find r_i and r_{i+1} that can maximize the value of $\min(e_i / (a+br_i^{\alpha}) , e_{i+1} / (a+br_{i+1}^{\alpha}))$ satisfying:

if $(\frac{a+br_i^{\alpha}}{a+bd^{\alpha}_{i,i+2}} < \theta_{acq})$ $r_{i+1} = d_{i+1,i+2}$;

if $(\frac{a+br_i^{\alpha}}{a+bd^{\alpha}_{i,i+2}} > \theta_{acq})$

$$r_{i+1} = \max((\frac{\theta_{acq}(a+bd^{\alpha}_{i+1,i+2})-a}{b})^{\frac{1}{\alpha}}, (((1-\frac{a+br_i^{\alpha}}{a+bd^{\alpha}_{i,i+2}})(a+bd^{\alpha}_{i+1,i+2})-a)/b)^{\frac{1}{\alpha}});$$

}

else { $r_i = d_{i,i+1}$;

if $(\frac{a+br_i^{\alpha}}{a+bd^{\alpha}_{i,i+2}} < \theta_{acq})$ $r_{i+1} = d_{i+1,i+2}$;

if $(\frac{a+br_i^{\alpha}}{a+bd^{\alpha}_{i,i+2}} > \theta_{acq})$

$$r_{i+1} = \max((\frac{\theta_{acq}(a+bd^{\alpha}_{i+1,i+2})-a}{b})^{\frac{1}{\alpha}}, (((1-\frac{a+br_i^{\alpha}}{a+bd^{\alpha}_{i,i+2}})(a+bd^{\alpha}_{i+1,i+2})-a)/b)^{\frac{1}{\alpha}});$$

}

n_i sets it's transmission range as r_i;

n_i sends n_{i+1} a message notifying it reset its transmission range as r_{i+1};

}

Figure 3 Localized algorithm for flows with fixed nodes

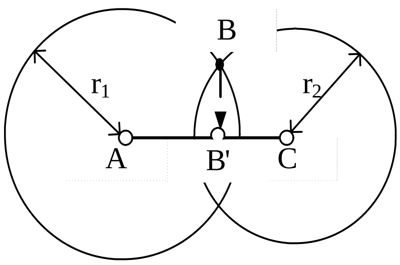

Figure 4 Node B moves to an optimal position nearer to node C

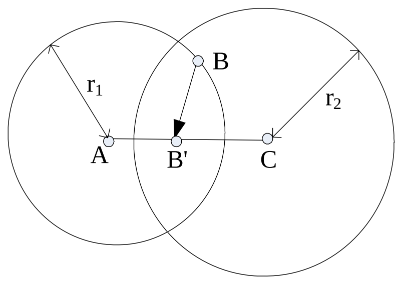

Figure 5 Node B moves to an optimal position further to node C

Assume there is a one-to-one flow containing only three nodes *A*, *B* and *C* in sequence, with their current locations (x_A, y_A), (x_B, y_B) and (x_C, y_C), and residual energy e_A, e_B and e_C respectively. Node B will move to a new position $B'(x_B', y_B')$, and the distance it moves across is denoted as $d_{BB'}$. $d_{AB'}$ denotes the distances between (x_B', y_B') and (x_A, y_A), and $d_{B'C}$ denotes the distances between (x_B', y_B') and (x_C, y_C). The protocol between node *A*, *B* is shown as:

1. Node *A* sends node *B* a message indicating its residual energy e_A;
2. Node *B* receives this message, takes its residual energy e_B into account, and then does as following:

1) If $e_A/(a+bd_{AB}^{\alpha}) > e_B/(a+bd_{BC}^{\alpha})$, then:

a) Node *B* will select an optimal position (x_B', y_B') nearer to node *C* to decrease its transmission power. When making certain the position by calculating $\frac{e_A}{e_B - k_m d_{BB'}} = \frac{a+bd_{AB}^{\alpha}}{a+bd_{BC}^{\alpha}}$ (the algorithm is given in figure (7)), node *B* uses the CC model to further calculate its and *A*'s new transmission power pow_B' and pow_A' respectively. Clearly, $pow_B' \le a+bd_{BC}^{\alpha}$.

b) For $pow_B' \le a+bd_{BC}^{\alpha}$, Node *B* remains its transmission power unchanged and sends node *A* a

Algorithm MultiFlowWithFixedNodes on node n_i {

n_i receives a message *m* from node n_{i-1}; *f* = n_i.getItsFlow(*m*);

$n_{i+1} = n_i$'s next node on the flow *f*;

$d_{i,i+1}$ = distance(n_i, n_{i+1}); $d_{i-1,i}$ = distance(n_i, n_{i-1}); $d_{i-1,i+1}$ = distance(n_{i-1}, n_{i+1});

n_i sends a message to node n_{i-1} inquiring its residual energy;

n_{i-1} sends a message recording its residual energy e_{i-1}

Then, n_i computes as the following process:

if($e_{i-1}/(a+bd_{i-1,i}^{\alpha}) > e_i/(a+bd_{i,i+1}^{\alpha})$)

for $d_{i,i+1} \le d_x \le d_{i,i+2}$ {

find d_x and d_y that can maximize the value of min($e_{i-1}/(a+bd_x^{\alpha})$, $e_i/(a+bd_y^{\alpha})$),

with the constraints:

if $\left(\frac{a+bd_x^{\alpha}}{a+bd_{i-1,i+1}^{\alpha}} < \theta_{acq}\right)$ $d_y = d_{i,i+1}$;

if $\left(\frac{a+bd_x^{\alpha}}{a+bd_{i-1,i+1}^{\alpha}} > \theta_{acq}\right)$

$d_y = \max\left(\left(\frac{\theta_{acq}(a+bd_{i,i+1}^{\alpha})-a}{b}\right)^{\frac{1}{\alpha}}, \left(\left(\left(1-\frac{a+bd_x^{\alpha}}{a+bd_{i-1,i+1}^{\alpha}}\right)(a+bd_{i,i+1}^{\alpha})-a\right)/b\right)^{\frac{1}{\alpha}}\right)$;

}

else { $d_x = d_{i-1,i}$;

if $\left(\frac{a+bd_x^{\alpha}}{a+bd_{i-1,i+1}^{\alpha}} < \theta_{acq}\right)$ $d_y = d_{i,i+1}$;

if $\left(\frac{a+bd_x^{\alpha}}{a+bd_{i-1,i+1}^{\alpha}} > \theta_{acq}\right)$

$d_y = \max\left(\left(\frac{\theta_{acq}(a+bd_{i,i+1}^{\alpha})-a}{b}\right)^{\frac{1}{\alpha}}, \left(\left(\left(1-\frac{a+bd_x^{\alpha}}{a+bd_{i-1,i+1}^{\alpha}}\right)(a+bd_{i,i+1}^{\alpha})-a\right)/b\right)^{\frac{1}{\alpha}}\right)$;

}

n_i sets its transmission range as d_y;

n_i sends n_{i+1} a message notifying it reset its transmission range as d_x;

}

Figure 6 Local algorithm for multi-flow with fixed nodes message indicating node A's new transmission power;

c) After receiving the message, node A sets its temporal transmission power $pow_A^t = \max(a+bd_{AB}^{\alpha}, a+bd_{AB'}^{\alpha}, pow_A')$. It sends node B an ACK message;

d) After receiving the message, node B begins to move to the next position;

e) After arriving at the optimal position, node B sends node A a message notifying it to reset the power $pow_A = pow_A'$ and sets the power of itself as $pow_B = pow_B'$.

The above process is presented in figure 4, where the r_1 denotes A's temporal transmission range with the value $Max(d_{AB}, d_{AB'}, ((pow_A' - a)/b)^{\frac{1}{\alpha}})$, and r_2 denotes B's temporal transmission range with the value $((pow_B - a)/b)^{\frac{1}{\alpha}}$. During node B's movement, if it is always in the two circles at the same time, clearly, the topology constraint for connectivity will not be violated.

2) If $e_A/(a+bd_{AB}^{\alpha}) < e_B/(a+bd_{BC}^{\alpha})$, then:

a) Node B will select an optimal position (x_B', y_B') farther to node C and nearer to node A to increase its transmission power and decreases node A's power. After making certain the position by calculating $\frac{e_A}{e_B - k_m d_{BB'}} = \frac{a+bd_{AB'}^{\alpha}}{a+bd_{B'C}^{\alpha}}$, node B uses the CC model to computing its and A's new transmission power pow_B' and pow_A' respectively. Then node B sets its temporal power as $pow_B^t = a+bd_{B'C}^{\alpha}$, and begins to move.

b) During node B's movement, node A remains its transmission power as $a+bd_{AB}^{\alpha}$;

c) After arriving at the optimal position, node B sends node A a message notifying it to reset the power $pow_A = pow_A'$ and sets the power of itself $pow_B = pow_B'$.

The above process is presented in figure 5, where the r_1 denotes A's temporal transmission range with the value $r_1 = (pow_A - a)/b)^{\frac{1}{\alpha}}$, and r_2 denotes B's temporal transmission range with the value $r_2 = ((pow_B^t - a)/b)^{\frac{1}{\alpha}}$. Clearly, during node B's movement, if it is always in the two circles at the same time, clearly, the topology constraint for connectivity will not be violated.

void FindNextPosition(Node n_i){

n_{i-1} is n_i's pre-neighbor on the flow;

n_{i+1} is n_i's next-neighbor on the flow;

(x_{i-1}, y_{i-1}) is n_{i-1}'s current position;

(x_{i+1}, y_{i+1}) is n_{i+1}'s current position;

for $x_{i-1} < x_B' < x_{i+1}$ and $y_{i-1} < y_B' < y_{i+1}$ {

if ($y_B' == \frac{y_{i+1} - y_{i-1}}{x_{i+1} - x_{i-1}} x_B' + \frac{y_{i-1}x_{i+1} - x_{i-1}y_{i+1}}{x_{i+1} - x_{i-1}}$)

and ($\frac{e_A}{e_B - k_m((x_B - x_B')^2 + (y_B - y_B')^2)^{\frac{1}{2}}} == \frac{a+b((x_B' - x_{i-1})^2 + (y_B' - y_{i-1})^2)^{\frac{\alpha}{2}}}{a+b((x_{i+1} - x_B')^2 + (y_{i+1} - y_B')^2)^{\frac{\alpha}{2}}}$)

n_i select its next position as (x_B', y_B');

}

Figure 7 The algorithm for calculating next position

4.4 Solutions for Multi-Flow with Mobile Nodes

In the scenario of multi-flow with mobile nodes in the ad hoc network, the nodes can move to their optimal positions individually. Different from the scenario of single-flow with mobile nodes, when a node on different flows (such as node n in figure 2) begins to move to its next optimal position, it will take all its neighbors' position and residual energy into account. In this scenario, a scheme is proposed to minimize the total energy consumption of all flows. Suppose now node n with the position (x_n, y_n)

is on *k* different flows. On each flow f_i, it has a preceding neighbour s_i with the positions (x_{S_i}, y_{S_i}), and a succeeding neighbour D_i with the positions (x_{D_i}, y_{D_i}). Each flow f_i has its traffic amount as w_i. d_{ij} is denoted as the Euclidean distance between node *i* and its succeeding neighbour *j*. Each node *i* has set its initial transmission power as $p(i,j) = a + bd_{ij}^{\alpha}$. When one neighbor sends the data to node *n* along f_i, node *n* sends it to the responding succeeding neighbor on f_i. The total power consumption is: $E_{total} = \sum_{i=1}^{k} w_i p(S_i, n) + \sum_{i=1}^{k} w_i p(n, D_i)$. When $\frac{\partial E_{total}}{\partial x_n} = 0, and \frac{\partial E_{total}}{\partial y_n} = 0$, the minimize value of E_{total} can be got. Thus, with $\alpha = 2$, the result is $x_n = (\sum_{i=1}^{k} w_i x_{S_i} + \sum_{i=1}^{k} w_i x_{D_i}) / 2\sum_{i=1}^{k} w_i$ and $y_n = (\sum_{i=1}^{k} w_i y_{S_i} + \sum_{i=1}^{k} w_i y_{D_i}) / 2\sum_{i=1}^{k} w_i$. By the analysis, a local algorithm for multi-flow is given in figure 8.

```
Algorithm MultiFlowWithMobileNodes on node n {
1)  n receives a message m from node n_{i-1} along a flow f_m;
2)  n_{i+1} is n 's next neighbor on flow f_m;
3)  (x_n, y_n) = n .getCurrentPosition();
4)  For each f_i where n is on {
5)     n sends a message to the preceding neighbor s_i and succeeding neighbor D_i respectively to
       inquire their positions and residual energy;
6)  }
7)  n computes its next optimal position n' = (x_n', y_n'). Here x_n' = (Σ_{i=1}^k w_i x_{S_i} + Σ_{i=1}^k w_i x_{D_i}) / 2Σ_{i=1}^k w_i and
    y_n' = (Σ_{i=1}^k w_i y_{S_i} + Σ_{i=1}^k w_i y_{D_i}) / 2Σ_{i=1}^k w_i ;
8)  E_total = Σ_{i=1}^k w_i p(S_i, n) + Σ_{i=1}^k w_i p(n, D_i) ;
9)  E_total' = Σ_{i=1}^k w_i (a + bd^α(S_i, n')) + Σ_{i=1}^k w_i (a + bd^α(n', D_i)) ;
10) if( E_total > k_m d(n, n') + E_total' ) {
11)    n moves to its optimal position (x_n', y_n') ;
12)    n communicates with n_{i-1} to determine their new transmission power according to the Algorithm
       MultiFlowWithFixedNodes.
13) }
14) else
15)    n communicates with n_{i-1} to determine their new transmission power according to the Algorithm
       MultiFlowWithFixedNodes;
16) }
```

Figure 8 Local algorithm for multi-flow with mobile nodes

5. Simulation Results

We set up a $100m \times 100m$ area with mobile nodes distributed in randomly. We randomly select two nodes as the source and destination of the flow. The number of nodes the flow containing vary from three to ten. Evaluation of comparing DEEF with other algorithms presented in [2], [5], [6], and [19] are given for testing system lifetime under different mechanisms. The different parameters' influences on the results under practical energy constraints are discussed in this section. The input parameters needed is listed in table 1 as follows:

Parameter	Value
Net Size	100mX100m
Node number in flow	10
a	50nJ/bit
b	13pJ/bit/m^2
α	2
Threshold distance(d_0)	75m
Flow length	[0.5MB, 640MB]
Packet header size	25 bytes
Mobile node's initial energy	[5J, 10J]
Threshold to decode the packet payload θ_p	1
Threshold for time acquisition $\theta_{\alpha cq}$	[0.1, 0.5]

Constant of mobility cost k_m	[0.1J, 1J]
Mobile node's initial transmission range	20m

Table 1 List of input parameters

Figure 9-11 show the influence of flow length on the energy consumption of single-to-single flow with fixed nodes not using CC model, and DEEF (in this test all the nodes are fixed in DEEF). In the tests, we set 25 bytes to the packet header size, let $\theta_{\alpha cq}$ vary in the set of {0.125, 0.25, 0.5}, let the flow length vary between [0.5MB, 64MB], and set mobile nodes' initial energy e_i in the domain of [5J, 10J] randomly. The results shown in the figures are the average value of one hundred times of simulations. We use the number of rounds (the process stops when the first node in the flow dies) to measure the system's life. Observed from figure 9, because the mobile node will consume more energy for data transmission, the lifetime of the two mechanisms decreases with the flow length increased. The lifetime of the flow using DEEF is averagely 75% longer than that of the flow not using CC model. For example, when the flow length is 2MB and $\theta_{\alpha cq}$ =0.125, the lifetime of the flow using DEEF is averagely 203 rounds, while the lifetime of the flow not using CC is only averagely 113 rounds. The reason is that in DEEF, the nodes that have more residual energy will increase their transmission power, thereby the nodes with less residual energy can diminish their transmission power. In this way, the lifetime of the flow is improved. Also seen from the figures, with $\theta_{\alpha cq}$ increasing, the life of the flow using CC has been decreased. However, $\theta_{\alpha cq}$ has little influence on the life of the flow not using CC.

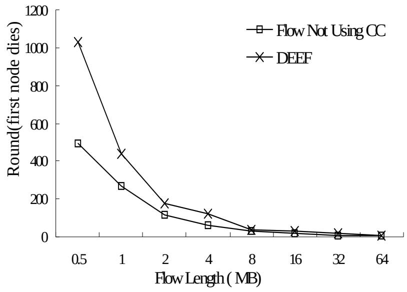

Figure 9 $\theta_{\alpha cq}$ =0.125

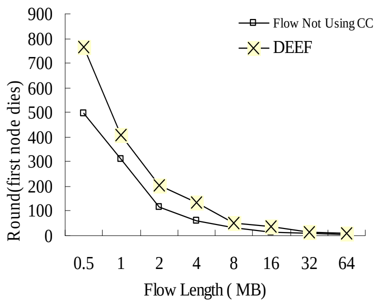

Figure 10 $\theta_{\alpha cq}$ =0.25

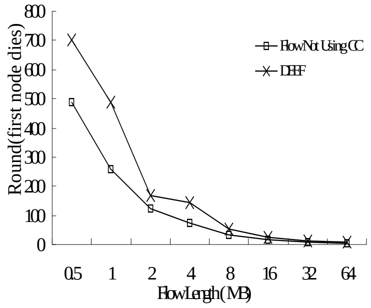

Figure 11 $\theta_{\alpha cq}$ =0.5

Figure 9-11 The influence of flow length

In figure 12-14, we test the influence of the number of nodes in a flow on its lifetime. In the simulation, we set $\theta_{\alpha cq}$ in the set of {0.125, 0.25, 0.5}, set 5MB to the flow length, and make the number of nodes in a flow increase from 3 to 10. Also, $\theta_{\alpha cq}$ has a negative influence on the lifetime of the flow using CC model. Observed from the figures, the flow using DEEF has a much longer lifetime than the flow not using CC model. However, when the number is three, there is little difference between the two mechanisms. The reason is that for the nodes' energy being set randomly, in the flow containing only three nodes, if the second node has more energy, the first node can't increase its power to partly cover the third node. In this way, DEEF can't show its efficiency. However, with the number of nodes in the flow increasing, DEEF shows its efficiency. Seen from figure 12, when the flow contains eight nodes, the lifetime of the flow using DEEF is about 88% higher than the flow not using CC model.

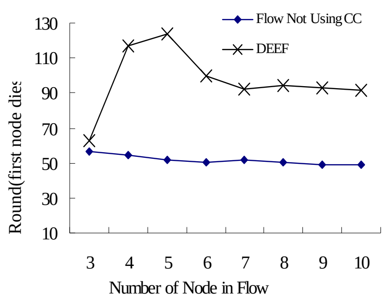

Figure 12 θ_{acq} =0.125

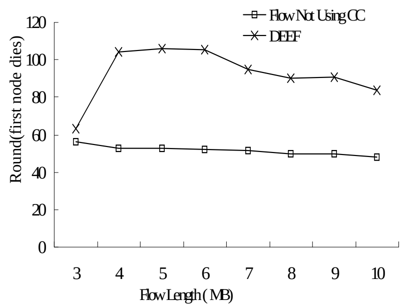

Figure 13 θ_{acq} =0.25

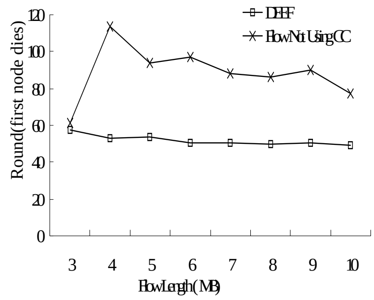

Figure 14 θ_{acq} =0. 5

Figure 12-14 The influence of node number

From figure 15 to 21, we compare DEEF with two other algorithms GA (global algorithm) and LA (localized algorithm) presented in [5]. In the tests, the nodes can move to their optimal positions according to their different protocols respectively. In figure 15-17, the influence of the flow length on the three mechanisms is tested. In this simulation, we create a flow containing ten nodes. The nodes' positions are distributed randomly, and their initial energy are also set randomly. θ_{acq} varies in the set of {0.125, 0.25, 0.5}, the flow length varies from 5MB to 640MB, and the mobility consumption is set to 0.1J/M. Seen from the figures, DEEF shows its higher efficiency than the other two algorithms. For example, in figure 15, when the flow length is 40MB, the lifetime of the flow using DEEF is averagely 140% higher than GA and LA. The reason is that in DEEF, the nodes having more energy can increase its transmission power, and the nodes with less energy will decrease their transmission power to save the energy. In GA and LA, because the nodes can't transmit data by the approach of partly covering, the nodes with less energy have to remain their transmission power unchanged to successfully transmit data directly to the next nodes on the flow.

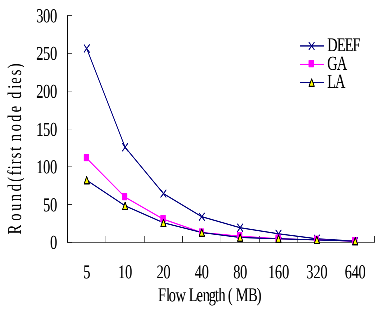

Figure 15 θ_{acq} =0.125

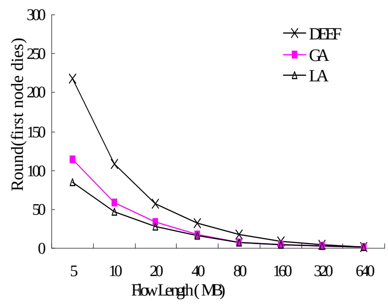

Figure 16 θ_{acq} =0.25

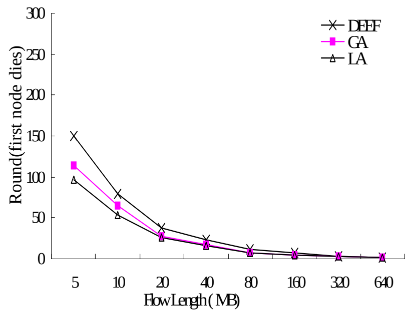

Figure 17 θ_{acq} =0.5

Figure 15-17 The influence of flow length on the three algorithms

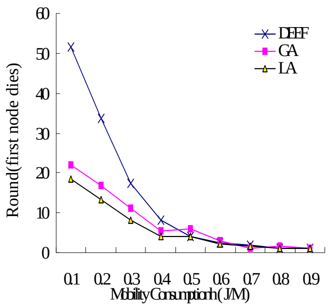

Figure 18 θ_{acq} =0.125

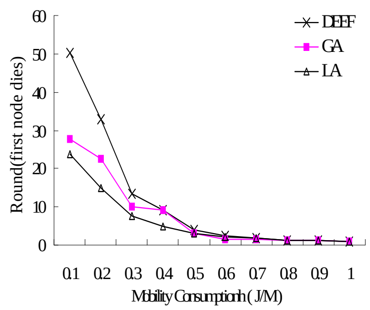

Figure 19 θ_{acq} =0.125

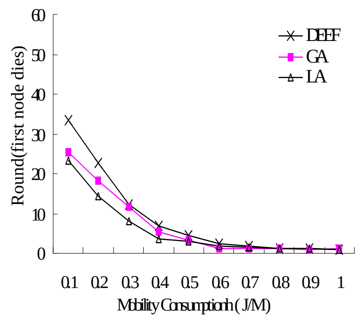

Figure 20 θ_{acq} =0.125

Figure 18-20 The influence of mobility cost on the three algorithms

Figure 18-20 show the influence of mobility cost k_m on the lifetime of the flows using the three different mechanisms. In the tests, we set 0.125 to $\theta_{\alpha cq}$, set the flow length 25MB, and let mobile nodes' initial energy e_i vary in the domain of [5J, 10J] randomly. In the simulation, the flow for testing contains ten mobile nodes. Each node on the flow has its location distributed randomly. The mobility cost varies from 0.1J/m to 0.9J/m. Seen from the figures, when the mobility cost is not high, DEEF shows it high efficiency. For example, when k_m =0.2, the lifetime of the flow using DEEF is about 100% higher than the flow using GA, and 154% higher than the flow using LA. However, when k_m increases to 0.5J/m, GA has more efficiency than DEEF. The reason is that in GA, all the nodes in the first round get to their optimal position and will not move again. While in DEEF and LA, the mobile nodes will move several times to get to their optimal positions. Thus, with k_m increasing beyond some value, the flow using GA has a longer lifetime than the flow using DEEF or LA.

Figure 21 shows the influence of the flow's node number on its lifetime. In the simulation, we set $\theta_{\alpha cq}$ = 0.125, set 5MB to the flow length, and make the number of nodes in flow increase from 3 to 10. Observed from the figure, when the number of nodes is 3, GA and LA show higher efficiency than DEEF. The reason is that, in the flow containing only three nodes, during the first round, the nodes in GA and LA can get to their most optimal locations, while in DEEF, since the energy of each node does not decrease linearly, the node has to move several times and this moving process consumes the nodes' energy. However, with the flow's node number increasing, DEEF shows its energy efficiency. For example, when the node number is eight, the lifetime of the flow using DEEF is about 137% higher than the flow using GA and 175% higher than the flow using LA.

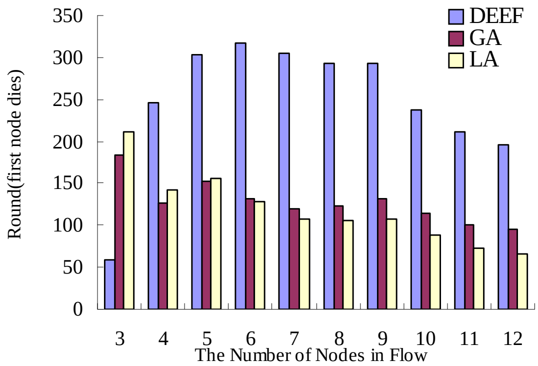

Figure 21 The influence of node number on the three algorithms

6. Conclusions

Controlled node mobility is an effective approach to reduce the communication energy consumption while the movement itself consumes energy. In order to reduce the energy consumption of data flows in the mobile ad hoc network, this paper uses cooperative communication (CC) models among mobile nodes and presents a localized mechanism named DEEF that can support data transmission in flow paths with less transmission power for each node. DEEF also help the nodes make local decision on their controlled mobility. By directing mobile node mobility and making them adapt their transmission power dynamically, our mechanism shows its efficiency in improving the system lifetime.

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