An Energy Efficient Select Optimal Neighbor Protocol for Wireless Ad Hoc Networks

Bao Hua Liu, Yang Gao, Chun Tung Chou, Sanjay Jha

Network Research Laboratory
School of Computer Science and Engineering
The University of New South Wales, Sydney, Australia

Email: {mliu, yangg, ctchou, sjha}@cse.unsw.edu.au

UNSW-CSE-TR-0431

October 20, 2004

THE UNIVERSITY OF
NEW SOUTH WALES

SYDNEY · AUSTRALIA

Abstract

In this paper, we propose two location-aware select optimal neighbor (SON) algorithms that are suitable for CSMA/CA based MAC protocols for wireless ad hoc networks. Both algorithms optimize the energy efficiency by reducing the effective number of neighbors and thus reduce the transmission power as well as the overhearing power consumption at irrelevant receivers. NS-2 simulations show that our algorithms can achieve about 28% and 38% average energy savings per node compared to CSMA/CA based MAC protocols such as IEEE 802.11. When electronic energy consumption is a considerable part of energy consumption, SON has a better energy performance than traditional optimal pruning algorithm.

1 Introduction

Wireless devices in ad hoc networks are normally powered by batteries. Batteries can only provide finite amount of energy. Therefore, it is important to design energy efficient protocols to reduce the unnecessary energy consumption in order to prolong the battery lifetime. This is especially important in wireless sensor networks where energy consumption is the primary concern. A number of protocols and algorithms have been proposed in literature [1][9][13][15] to reduce the energy consumption for wireless ad hoc networks. This paper proposes two energy efficient neighbor selection algorithms that can work with CSMA/CA based MAC protocols.

IEEE 802.11 is the de facto MAC protocol for wireless LANs and ad hoc networks. But IEEE 802.11 suffers from power inefficiency and low throughput in high traffic load scenario. Different topology control protocols with the goal of increasing throughput as well as reducing energy consumption have been proposed in literature [2][4][5][6][8]. The major technique employed in these protocols is to reduce the transmission power to control the number of neighbors while still maintaining the network connectivity. For example, Blough *et al.* [8] proposed a *K-Neigh* protocol to maintain the network connectivity with high probability, where each node keeps up to nine nearest nodes as neighbors and removes the neighbors with unidirectional links. An optimized pruning algorithm (denoted as TOPA in this paper and is shown in Algorithm 1) is then executed to reduce the energy inefficient nodes from neighbor list.

> Let $P(i, j)$ denotes the transmission power for node i to reach node j and node i has a sorted (according to increasing value of $P(i, j)$) neighbor list as $j_1, j_2, \ldots, j_k$. For $l = 2, \ldots, k$, do the following:
> *1.* Check whether j_l can be reached using a transmission power lower than P_{i,j_l} by routing through some j_q, where $q < l$.
> *2.* If $P(i, j_q) + P(j_q, j_l) \leq P(i, j_l)$, logically delete link (i, j_l) and remove node j_l from the neighbor list.
> *3.* Set the transmission power of i to the power needed to reach the farthest node in its neighbor list.

Algorithm 1: Traditional optimized pruning algorithm(TOPA).

Muqattash and Krunz [2] proposed a similar pruning algorithm. The authors claimed that in addition to improving network throughput, reducing the transmission range plays an important role in reducing the energy consumption. Rodoplu and Meng [3] have showed that power-efficient routes can be found by considering only the nodes in the *enclosure region* as potential next hops. Another advantage of power control that has not received much attention in the literature is related to reducing the power consumption at *irrelevant receivers* (those who are not addressed by the transmission). Since reducing transmission range results in a smaller number of nodes overhearing the transmission, less receiving power will be consumed by these irrelevant receivers [2].

Our work can be treated as an alternative to the above mentioned pruning algorithm and complementary to those topology control protocols. The main contribution of this paper is that our algorithms consider not only the energy consumption at transmitter and intended receiver, but also the energy consumption at those irrelevant (or interfered) receivers. We also demonstrate that the correctness of the *K-Neigh* pruning algorithm is questionable if the transmission power is not adjusted to reach different neighbors. We show that only when each node can adjust its power levels to communicate with different neighbors then the pruning algorithm can make energy savings.

The rest of this paper is organized as follows. Section 2 elaborates the proposed algorithm design. Section 3 provides simulations and analysis. Section 4 describes related work. We conclude our paper in Section 5.

2 The Algorithm Design

Our proposed algorithm includes six phases as shown in Figure 1. These phases are: *node startup, location broadcast, power allocation table (PAT) broadcast, select optimal neighbor (SON), symmetrization, and normal operation*. The SON related actions begin from *location broadcast* and end at *symmetrization*. We also make the following assumptions:

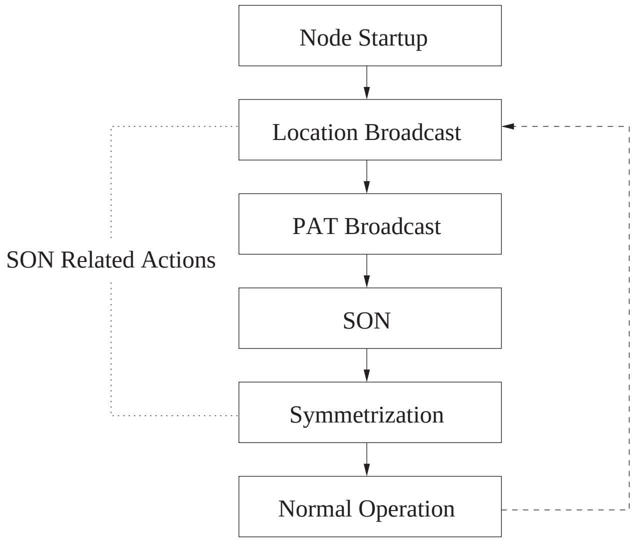

Figure 1: Proposed algorithm phases

- Network topology is quasi-static so the introduced overheads are not very severe.
- Each node can estimate its location or its relative location.
- Each node can adjust its transmission power to reach different neighbors.

2.1 Location Broadcast

In location broadcast phase, each node broadcasts its location information with its full radio power. As aforementioned, we assume that each node can estimate its location. This can be achieved by using some remote infrastructures such as GPS. However, in our protocol design, absolute location information is not necessary and relative locations can be used. The relative location information can be estimated through the measurements of signal strength from a beacon node [10] or some other approach [12].

In CSMA/CA based MAC protocols, RTS/CTS are normally not used for broadcast packets. To guarantee that each node can get an opportunity for a successful transmission, we employ large contention windows and allow each node to broadcast several times. Blough *et al.* [8] proved the crude lower bound that no contentions occur in a wireless channel with following lemma:

Lemma 1 *Let $\bar{t}$ be the time necessary to transmit a packet. For $d = m\bar{t}$, the probability that no contention will occur in a wireless channel is strictly grater than $exp(-\frac{3h(h-1)}{2m})$, where h denotes the number of nodes that are contending for the channel.*

An example was also given in [8] with 33 contending nodes, where d must be around $16000\bar{t}$ to achieve a probabilistic guarantee of no contention of at least 0.9. With $\bar{t}$ in the order of millisecond, d is around tenth of seconds. In practice, small values can be used.

At the end of *location broadcast* phase, each node (denote as *seed node*) can construct a neighbor list that contains all its radio range neighbors and their correspondent power levels for seed node to reach each of them. We call this *power allocation table (PAT)*, in which all neighbors are ranked according to the distance to the seed, and the correspondent power levels are estimated based on the distance and path loss exponent. A PAT after location broadcast is shown in Figure 2.

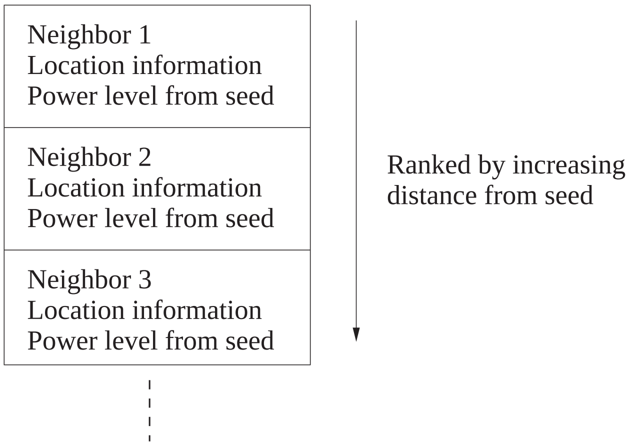

Figure 2: A PAT after location broadcast

2.2 Power Allocation Table Broadcast

Select optimal neighbor (SON) pruning algorithm not only considers the power consumption of transmitter and the intended receiver, but also the overhearing power consumption of other irrelevant neighbors that are affected by the transmission. To make SON functional, each node should have more information about its neighbors and their correspondent power allocation information. In this phase, each node broadcasts its power allocation table to its radio range neighbors. At the end of this phase, the corresponding power allocation information will be added to the records in each node's power allocation table. An example of the power allocation table after the PAT broadcast phase is shown in Figure 3.

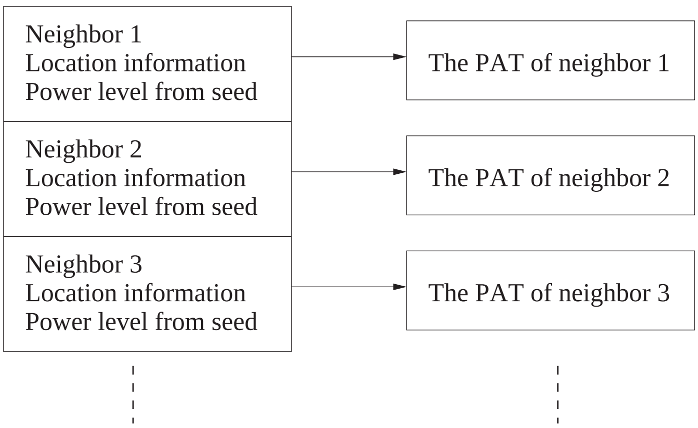

Figure 3: A PAT after PAT broadcast

2.3 Select Optimal Neighbor

In this session, we elaborate the SON algorithm in detail. We adopted a simple energy dissipation model that is used in LEACH [14]. The model is shown in figure 4. This model separates the electronic energy consumption and power amplifier energy consumption at the transmitter side. We next define some notation that will be used in our discussion. Let **E** denote the total energy consumption when transmitting a packet from a node to one of its neighbors, $ETX(ij)$ is the power amplifier energy consumption when node i is transmitting a packet to node j, ETX_{elec} is the radio electronic energy consumption when a node is transmitting

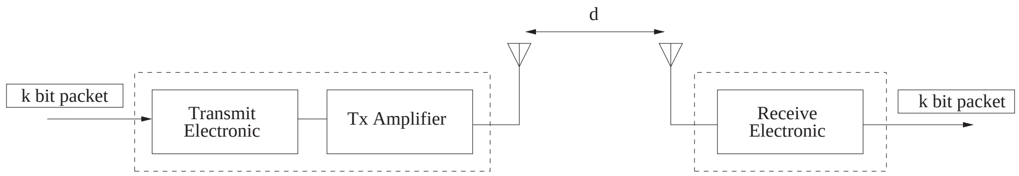

Figure 4: Radio energy dissipation model

a packet, and ERX_{elec}[1] is the radio electronic energy consumption when a node is receiving a packet. With these notation, the power amplifier energy consumption represents the distance-dependent power drawn. Let $P_r(d)$ the power of a given signal at a distance d from the transmitter of the signal, then $P_r(d) = P_t c/d^n$, where P_t is the transmission power from the transmitter, $2 \leq n \leq 6$ represents the path loss exponent, and c is a constant defined by system loss, antenna gain and wavelength. The radio electronic energy consumption represents the static (distance-independent) power drawn such as digital coding, modulation, and filtering of the signal before it is sent to the power amplifier.

With CSMA/CA based MAC protocols such as IEEE 802.11, each node regards all the nodes within its radio range as neighbors. We use Figure 5 to illustrate the idea of SON. Figure 5 shows twenty nodes that are

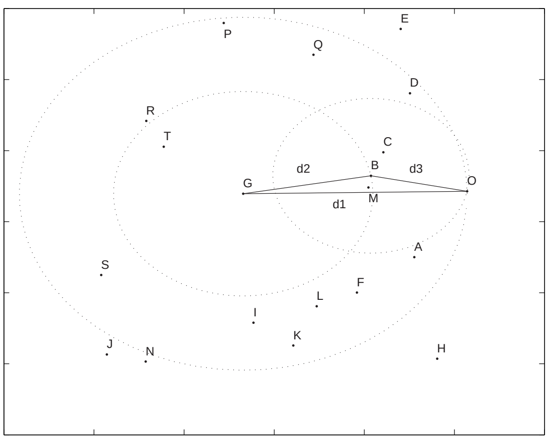

Figure 5: An SON example

randomly scattered in the area. Before using SON, both node B and node O are neighbors of node G. When a packet is directly transmitted from node G to node O, the total energy consumption can be expressed as

$$\mathbf{E}^{direct}(G,O) = ETX(G,O) + ETX_{elec} + ERX_{elec} \times (IN(G,O)+1) \tag{1}$$

where $IN(G,O)$ represents the number of interfered neighbors that will receive this packet and consume receiving energy when node G transmits a packet to O directly. After using SON, the packet is transmitted indirectly from node G to node O through node B, the total energy consumption is

$$\mathbf{E}^{indirect}(G,O) = \mathbf{E}^{direct}(G,B) + \mathbf{E}^{direct}(B,O) \tag{2}$$

where

$$\mathbf{E}^{direct}(G,B) = ETX(G,B) + ETX_{elec} + ERX_{elec} \times (IN(G,B)+1) \tag{3}$$
$$\mathbf{E}^{direct}(B,O) = ETX(B,O) + ETX_{elec} + ERX_{elec} \times (IN(B,O)+1) \tag{4}$$

[1]We assume that ERX_{elec} (ETX_{elec}) represents the difference between normal Rx (Tx) energy consumption and idle energy consumption.

where $IN(G, B)$ ($IN(B, O)$) represents the number of interfered neighbors that will receive this packet and consume receiving energy for a direct transmission from node G (B) to node B (O). In this case, we can see that for a direct transmission from G to O, there are 16 nodes (including the intended receiver O) which will receive this packet. For the indirect transmission from G to B to O, the total number of nodes that will receive the packet reduces to 8 (4 for $G \rightarrow B$ and 4 for $B \rightarrow O$). If $\mathbf{E}^{indirect}(G, O) < \mathbf{E}^{direct}(G, O)$ holds, which means the total energy consumed for the indirect transmission is less than the direct transmission, node G should not select node O as its neighbor.

Further our notation definition, let $PTX(ij)$ denotes the transmission power sufficient for node i to reach node j, PTX_{elec} the radio electronic power consumption when a node is transmitting, PRX_{elec} the radio electronic power consumption when a node is receiving. Let $IN(ij)$ denote the number of *interfered* neighbors of node i when node i is transmitting a packet to its neighbor j. The total energy cost for the direct transmission from node i to node j is

$$\mathbf{E}^{direct}(ij) = ETX(ij) + ETX_{elec} + ERX_{elec} \times (IN(ij) + 1) \tag{5}$$

Assume that the transmission time of a packet is T, then $ETX(ij) = PTX(ij) \times T$, $ETX_{elec} = PTX_{elec} \times T$, and $ERX_{elec} = PRX_{elec} \times T$. Now assume that node i has another neighbor node k, whose radio power level is less than j's (means k ranked before node j in the PAT of node i). Let

$$\mathbf{E}^{indirect}(ij) = \mathbf{E}^{direct}(ik) + \mathbf{E}^{direct}(kj) \tag{6}$$

If $\mathbf{E}^{direct}(ij) > \mathbf{E}^{indirect}(ij)$ hold, we can get

$$\begin{aligned} PTX(ij) + PRX_{elec} \times IN(ij) > PTX(ik) + PTX(kj) + PTX_{elec} + \\ PRX_{elec} \times (IN(ik) + IN(kj) + 1) \end{aligned} \tag{7}$$

Above inequality is used to determine if node i should select node j as its neighbor in the SON pruning process.

In this paper, we consider two derivatives of SON algorithm based on equation 7. For the first derivative, each node keeps all of its k nearest neighbors according to distance (or power level) if the kth neighbor can not be removed based on equation 7. We call it *select closest optimal neighbor (SCON)* algorithm. For the second derivative, each node only keeps the neighbors that are the most energy efficient based on equation 7. We call it *select energy efficient optimal neighbor (SEEON)* algorithm. These two algorithms are similar, but for one important difference which is illustrated with following example. Assume that a node has PAT (or neighbor list) as A, B, C, D, E, F, G, H and H is the farthest node that can not be removed according to equation 7, but E and F can be removed according to equation 7. This is possible if all the nodes are randomly scattered. With SCON approach, both E and F are kept in the neighbor list. On the contrary, E and F are removed from the neighbor list with SEEON approach.

We now describe the SON algorithm. Let $G = (V, E)$ be an undirected graph where V denotes the finite sets of nodes and E denotes the finite sets of edges (links), $i, j \in V$ and assume j is a one-hop neighbor of i before SON. PAT_i is the power allocation table of node i. For any node k in PAT_i, PAT'_k is the power allocation information of node k. Assume PAT_i contains n elements. The SON algorithm is shown in Algorithm 2.

We can see the difference between SCON and SEEON clearly. For SCON, a node stops checking other neighbors to be pruned if it can not remove a node in the neighbor list. However, SEEON checks all the neighbors from last one to second one and removes all the nodes that are not energy efficient. Note the pruning process starts from the last node in the neighbor list and goes upward until the second one.

One concern of removing nodes from neighbor list, which equals to removing links from a graph, is that it may change the network connectivity. However, we can prove that SON algorithm does not change the network connectivity with following definition and lemma.

Definition 1 *Let V denotes the finite set of nodes and E denotes the finite set of edges in a graph. Let $G = (V, E)$ an undirected graph such that there is an edge $e = (u, v)$ if and only if nodes u and v are*

```
input   : A PAT of all its neighbors and corresponding PAT of each neighbor
output  : An optimized neighbor list
for j ← n to 2 do
    isNeighbor = true ;
    get PTX(ij), IN(ij) from PAT_i;
    P(ij) = PTX(ij) + IN(ij) × PRX_elec;
    for k ← 1 to j − 1 do
        get PTX(ik), IN(ik) from PAT_i;
        P(ik) = PTX(ik) + IN(ik) × PRX_elec;
        if j ∈ PAT'_k then
            get PTX(kj), IN(kj) from PAT'_k;
            P(kj) = PTX(kj) + IN(kj) × PRX_elec;
            if P(ij) > P(ik) + P(kj) + PTX_elec + PRX_elec then
                isNeighbor = false ;
                break ;
            end
        end
    end
    // With SCON ;
    if isNeighbor = false then
        remove j from PAT_i;
    else
        break ;
    end
    // With SEEON ;
    if isNeighbor = false then
        remove j from PAT_i;
    end
end
```

Algorithm 2: Select optimal neighbor algorithm.

one-hop neighbors, where $u, v \in V$. The graph G is said to be connected if every pair of nodes is connected by a path, that is, every node is reachable from every other node.

Lemma 2 *Let $G = (V, E)$ an undirected graph before using SON algorithm. Let $G' = (V, E')$ the undirected graph constructed after using SON algorithm. If G is connected, then G' is connected.*

Proof: For any link $e = (u, v)$ and $e \in E$, $\mathbf{E}(e)$ denotes the energy consumption on the transmitter, the intended and irrelevant receivers when a packet is sending from u to v. Let A denotes the set of links which should be removed from graph G according to SON algorithm so we have $A = (E - E')$. Assume that there are k links belong to set A. We introduce the following algorithm to prove our lemma. In this algorithm, the links in A are removed in order. For $i = 1, 2, \ldots k$, let e'_i ($e'_i \in A$) denote the ith link that will be removed and $G_i = (V, E_i)$ denote the graph left after removing e'_i. Each time we remove the link $e'_i \in A$ which satisfies that $e'_i \in (A \cap E_{i-1})$ and $\mathbf{E}(e'_i) \geq \mathbf{E}(e') \quad \forall e' \in (A \cap E_{i-1})$ in the graph.

1. When $i = 1$ and $e'_1 = (u_1, v_1)$, there must be $m_1 \in V$ which can satisfy $e_1 = (u_1, m_1)$, $e_2 = (m_1, v_1)$ and $\mathbf{E}(e'_1) > \mathbf{E}(e_1) + \mathbf{E}(e_2)$ according to the SON algorithm. Because only one link is removed from E, we can get that $e_1, e_2 \in E_1$. So the connectivity of G_1 is same as that of G.

2. We assume that the connectivity of G_i keeps the same connectivity with that of G. After removing $e'_{i+1} = (u_{i+1}, v_{i+1})$. There must be $m_{i+1} \in V$ which can satisfy $e_l = (u_{i+1}, m_{i+1})$, $e_j = (m_{i+1}, v_{i+1})$ and $\mathbf{E}(e'_{i+1}) > \mathbf{E}(e_l) + \mathbf{E}(e_j)$. Because $\mathbf{E}(e'_{i+1}) > \mathbf{E}(e_l) \quad \mathbf{E}(e'_{i+1}) > \mathbf{E}(e_j)$ and we remove links in sequence from maximum to minimum $\mathbf{E}(e')$ in set A, we have $e_l, e_j \in E_{i+1}$. The connectivity of G_{i+1} is same as that of G_i and G. As a result, we can get the conclusion that the connectivity of G' is as same as G.

3. Let $G'' = (V, E'')$ denote the undirected graph in which n links have been randomly removed according SON algorithms. We can get that $E' \subseteq E''$. Because the connectivity of G' is as same as G, the connectivity of G'' must be as same as G. Finally, we proved that SON algorithm does not change the network connectivity.

2.4 Symmetrization

Because the network topology is random and asymmetric, it is possible that node A regards node B as its neighbor but node B does not regard node A as a neighbor. In the last phase, we allow each node to remove those neighbors with unidirectional links. Although implementing unidirectional links is technically feasible, the actual advantage of using unidirectional links is questionable [8]. Marina and Das [16] have shown that high overhead needed to handle unidirectional links in routing protocols outweighs the benefit that they provide, and better performance can be achieved by simply removing unidirectional links. In our NS-2 simulation, we found similar problems without implementing this last phase. When we use DSDV routing protocol, a node constructs its routing table depending on the DSDV routing messages it received. As a result, a node may receive some DSDV messages from its neighbors with unidirectional links and construct some links that it can not reach. When it routes packets through these unreachable links, it has to re-construct a new reachable link that consumes more overheads than normal routing.

In the *symmetrization* phase, each node broadcasts its neighbor list again with full radio power. When node A receives a broadcast packet from node B (assume B is in A's neighbor list), A will remove B from its neighbor list if B's neighbor list does not include A.

However, symmetrization may change broadcast radio power of the node (refer to Figure 12). The consequence is that the broadcast radio power of SCON and SEEON may be different after this phase. For example, assume that node A has PAT as B, C, D, E, F, G, H and H has a PAT as I, J, K, L, A, M after SCON. But node A has PAT as B, E, F, G, H and H has I, J, L, M (note A is not in H's PAT) after SEEON. After symmetrization phase, the PAT of A for SCON is B, C, D, E, F, G, H, but the PAT of A for SEEON is B, C, D, E, F, G (note H is removed from A's PAT because A is not in H's PAT). The farthest neighbor of A is H for SCON but G for SEEON. In this situation, the broadcast radio power of SEEON is different with that of SCON.

2.5 The Need to Adjust Transmission Power

The previous section presents an algorithm which allows a node i to choose an energy efficient set of neighbours $N(i)$. In this section, we investigate the power level that should be used to reach the nodes in $N(i)$. There are two options. For the first option, node i uses only one power level to reach all the nodes in $N(i)$. The power level is chosen so that it is just sufficient to reach the furthest node in $N(i)$. Note that this option is adopted by the power control algorithm described in Section 1. For the second option, node i uses a different power levels to reach different neighbors in $N(i)$. In fact, for each node j in $N(i)$, node i uses a power level which is just enough to reach node j. We will argue that the first option is flawed and may not produce any energy saving.

Assuming that the first option is used. Let nodes i, j, k be three nodes which satisfy $\mathbf{E}^{direct}(ij) > \mathbf{E}^{indirect}(ij) = \mathbf{E}^{direct}(ik) + \mathbf{E}^{direct}(kj)$. Thus, node j will be eliminated from the neighbor list of i by SON. Let p and q be, respectively, the furthest node in the neighbor list of i and j after SON is applied. With option 1, an indirect transmission from node i to node j costs $\tilde{\mathbf{E}}^{indirect}(ij)$, where

$$\tilde{\mathbf{E}}^{indirect}(ij) = \mathbf{E}^{direct}(ip) + \mathbf{E}^{direct}(kq) \quad (8)$$

By the definition of p and q, it can easily be shown that $\mathbf{E}^{direct}(ip) \geq \mathbf{E}^{direct}(ik)$ and $\mathbf{E}^{direct}(kq) \geq \mathbf{E}^{direct}(kj)$. Therefore we have

$$\tilde{\mathbf{E}}^{indirect}(ij) \geq \mathbf{E}^{indirect}(ij) \quad (9)$$

Since we already have $\mathbf{E}^{direct}(ij) \geq \mathbf{E}^{indirect}(ij)$, it is possible that $\tilde{\mathbf{E}}^{indirect}(ij) > \mathbf{E}^{direct}(ij)$ and if this holds, it means that the first option does not produce any energy savings. We next give an example to demonstrate that this may occur.

Let P_{th} and r_m denote respectively the receiving threshold and the maximum transmission range. The transmission power required to reach a node at distance r is $P_{th}r^n$ where n is the path loss exponent. Consider Figure 6 and we assume that there are x nodes clustered around p (e.g., from a to b). It can be shown that

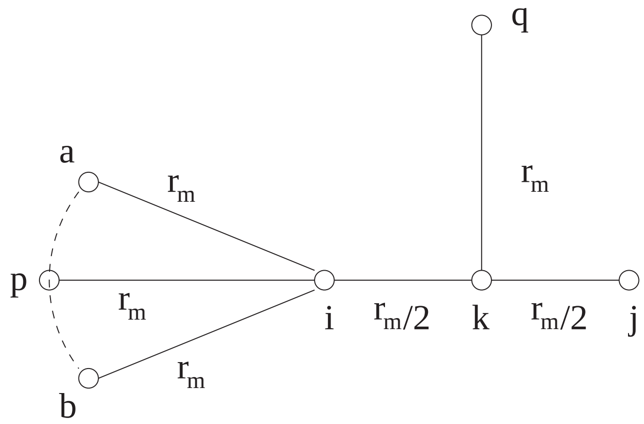

Figure 6: Negative effect without adjusting transmission power

$$\mathbf{E}^{direct}(ij) = P_{th}r_m^n + ETX_{elec} + (2+x)ERX_{elec} \quad (10)$$

$$\mathbf{E}^{indirect}(ij) = 2P_{th}(\frac{r_m}{2})^n + 2ETX_{elec} + 3ERX_{elec} \quad (11)$$

with a sufficiently large value of x and r_m, $\mathbf{E}^{direct}(ij) > \mathbf{E}^{indirect}(ij)$ holds. If transmission power is not adjusted, both nodes i and k will still be using the full transmission power in the indirect transmission from i to j, thus

$$\tilde{\mathbf{E}}^{indirect}(ij) = 2P_{th}r_m^n + 2ETX_{elec} + (5+x)ERX_{elec} \quad (12)$$

Comparing equations 11 and 12, we have $\tilde{\mathbf{E}}^{indirect}(ij) > \mathbf{E}^{direct}(ij)$ which means the indirect transmission costs more energy than the direct transmission. This contradicts directly with the aim of SON. Therefore, we can conclude that option one mentioned above is problematic.

For a network with large number of randomly deployed nodes, both $\tilde{\mathbf{E}}^{indirect}(ij) \geq \mathbf{E}^{direct}(ij)$ and $\tilde{\mathbf{E}}^{indirect}(ij) \leq \mathbf{E}^{direct}(ij)$ can exist. The positive and negative effects are balanced so that the energy consumption may not achieve sensible differences with and without SCON. Our simulation (refer to Figure 14) shows that the energy consumption of standard 802.11 and 802.11 with option one are almost the same.

Although the above argument takes irrelevant receivers into account, the same argument can also be applied to the *K-Neigh* pruning algorithm which does not consider irrelevant receivers. The conclusion is that varying the transmission power for each neighbor node is essential for energy savings.

3 Simulations and Analysis

A NS-2 simulation testbed has been implemented. The simulations focus on the network topology, connection between neighbors, and energy consumption. The energy dissipation model of Figure 4 is used in our simulation. In section 3.1, we use the Lucent IEEE 802.11 WaveLAN card parameters [1] and compare the performances between 802.11 and SON. In section 3.2, we use different electronic power values to evaluate the effect of the ratio between electronic power and the transmission power on the energy performance.

3.1 Simulations Using Constant Electronic Power

We use Lucent IEEE 802.11 WaveLAN card parameters [1] where the power consumption at transmit, receive, and idle are 1.65W, 1.4W and 1.15W respectively. The ETX_{elec} and ERX_{elec} used in the algorithm (equation 7) are the differences over the idle energy consumption. The parameters used in our simulations are shown in Table 1[2]. We implemented a random multi-hop network topology with 100 nodes randomly

Table 1: Parameters used in simulations.

Data Packet Size	2KB
Data Rate	2Mbps
Propagation Model	Log distance path loss
Reference Distance	1 meter
Path Loss Exponent	3
Antenna Gain	1
System Loss	l
Rx Threshold	1e-10 W
Rx Elec Power	250 mW
Tx Elec Power	250 mW
Max Radio Power	250 mW

deployed in $500m \times 500m$ square area and compared the energy consumption of 5 different algorithms: 1) standard 802.11 where the maximum transmission power is always used; 2) power adjustable 802.11 where different transmission power is used to reach different neighbor[3]; 3) power unadjustable SCON which is equivalent to TOPA; 4) SCON; and 5) SEEON. The power unadjustable SCON sets the Tx power needed to reach the farthest immediate neighbor. The network topology before SON is showed in Figure 7 and the topologies after SCON and SEEON are shown in Figure 8 and Figure 9. Comparing the three diagrams, we can see that the connection patterns are much simpler after SCON and SEEON.

Figure 10 shows the number of neighbors of each node before and after SON. The average number of

[2]Note that the ERX_{elec} is the difference between the real Rx power (1.4W) and idle power (1.15W). We assume that ETX_{elec} is same as ERX_{elec} and the idle energy is set to zero.

[3]The power is chosen such that when it reaches the intended receiver, the received power equals to the lowest receiving threshold.

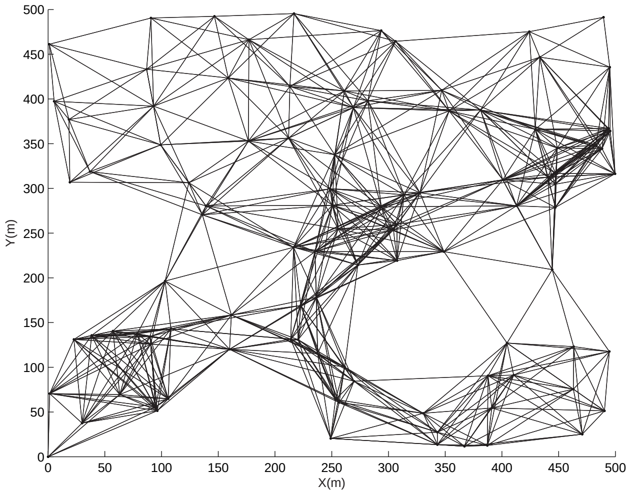

Figure 7: Network topology before SON

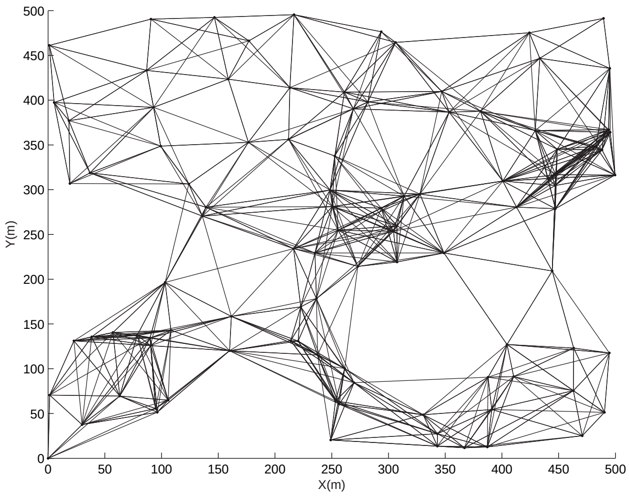

Figure 8: Network topology after SCON

neighbors decreases from 13.52 to 7.98 (SCON) and 5.78 (SEEON). The number of neighbors of some nodes reduce significantly. For instance, we found node 28 has 19 neighbors before SON but only 6 after SCON and SEEON. Node 54 has 14 neighbors before SON but only 4 neighbors after SCON and 3 neighbors after SEEON. As we described before, the neighbors of each node after SEEON is a subset of that after SCON. We can see that the number of neighbors of each node after SEEON is less than or equal to that after SCON.

Figure 11 shows the average radio power of each node when it communicates with its immediate neighbors. For standard 802.11, the nodes use maximum radio power (250mW) to transmit packet to neighbors. If we assume that the radio power can be adjusted depending on the distance of each node (power adjustable 802.11), the average power level decreases to 86.9mW which is only 34.8% of the standard 802.11. After SCON, the average power level decreases to 53.4 mW which is only 21.4% of the standard 802.11. For SEEON, the average radio power is 42.8mW and 17.1% of the standard 802.11. The difference in average radio power between SCON and SEEON is due to the symmetrization process we discussed in section 2.4.

Figure 12 shows the broadcast radio power of different protocols. The standard 802.11 still uses 250mW to broadcast packets. The power adjustable 802.11 uses the power needed to reach the farthest neighbor as its broadcast power, the average value decreases to 229.8 mW and is 9.1% less than standard 802.11. The average broadcast power of SCON decreased to 126.9 mW and is 49.2% less than standard 802.11. The

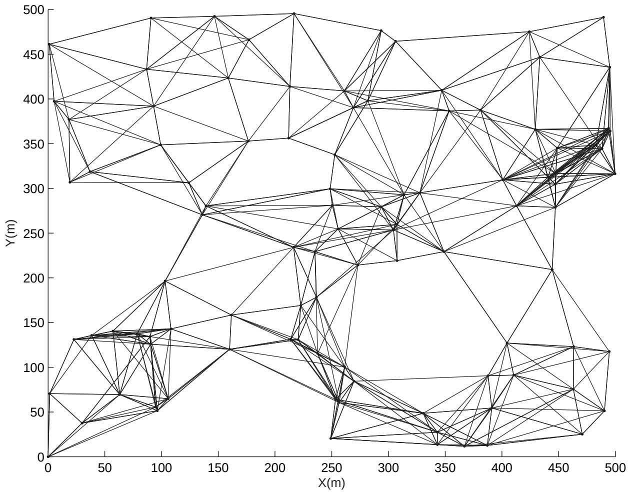

Figure 9: Network topology after SEEON

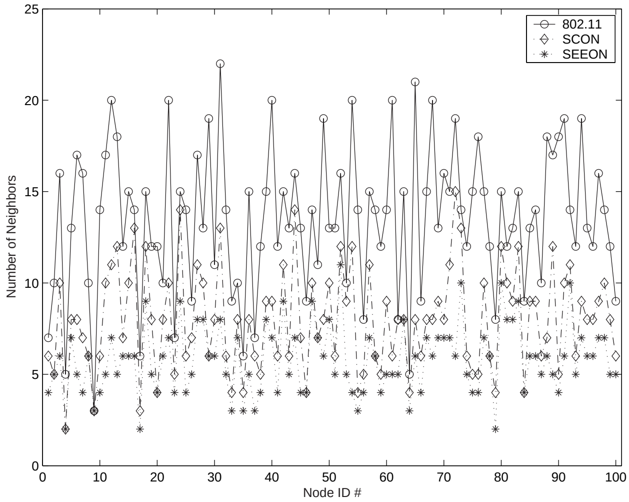

Figure 10: The number of neighbors of each node

average broadcast power of SEEON is 103.9 and is 58.5% less than standard 802.11. The difference in broadcast radio power between SCON and SEEON is also due to the symmetrization process.

In the simulation, we implemented 5 pairs of sources and sinks (randomly selected) with each source sending 100 packets to the correspondent sink. Each packet's departure time is randomized according to a uniform distribution (refer to NS-2 manual). DSDV routing protocol is used. Before transmitting data, we let each node exchange DSDV routing messages to construct its routing table. To avoid the influence of the DSDV energy consumption on our evaluation of the SON, we only set the network to exchange DSDV routing messages once and keep the same routes when the packets are transmitted. Figure 13 shows the average energy consumption per node for a full process of DSDV information exchange for the whole network. Both standard 802.11 and power adjustable 802.11 used 6369 messages to exchange DSDV routing information. The power adjustable 802.11 consumed on average 0.4273J per node and is about 0.6% less than standard 802.11 (0.4297J). SCON exchanged 7435 messages and consumed 0.3313J per node. SEEON exchanged 8205 messages and consumed about 0.3200J per node. Because SCON and SEEON have smaller broadcast radio powers and less number of neighbors, they used 16.7% and 28.8% more messages than 802.11 to make each node obtain the same topology information of the whole network. However, they achieved about 22.9% and 25.5% energy savings than standard 802.11. We can see that SON has better energy performance when

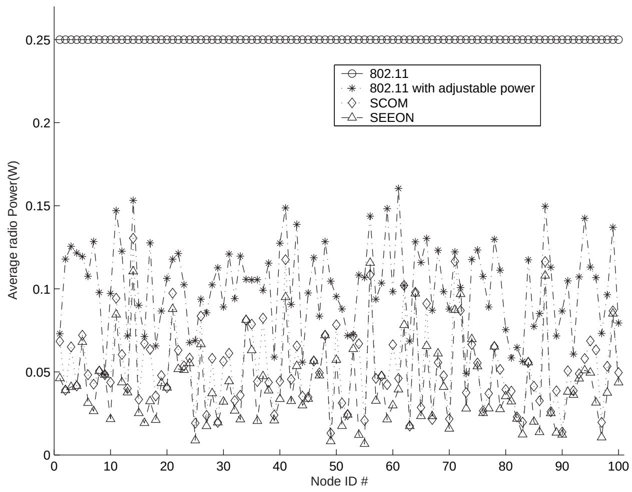

Figure 11: Average radio power to communicate with neighbors

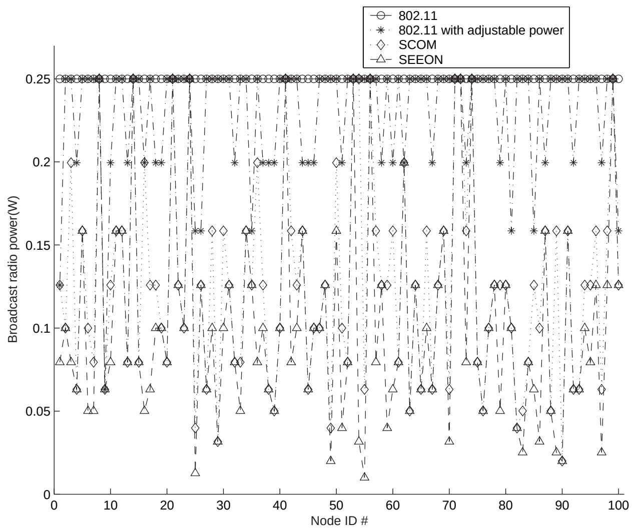

Figure 12: Broadcast radio power of each node

the network exchange information using broadcast.

Figure 14 shows the average energy consumption per node for data transmission. The average energy consumption per node are 1.519J (standard 802.11), 1.242J(power adjustable 802.11), 1.475J (power unadjustable SCON), 1.095J (SCON) and 0.937J (SEEON). From the simulation, we can see that the energy consumption of power unadjustable SCON is only 2.9% less than standard 802.11. This result proved our suspicion in section 2.5. However, we can achieve 27.9% energy savings than standard 802.11 if we assume power adjustable SCON. To make sure that the energy savings is not only due to the adjusting power but also our select optimal neighbor algorithms, we compared SCON and SEEON with power adjustable 802.11. We can see that SCON and SEEON achieved 11.8% and 24.6% energy savings compare with power adjustable 802.11 and 27.9% and 38.3% energy saving compared with standard 802.11.

3.2 Simulations Using Different Electronic Power

From equation 5 and equation 7, we can see that the network topology after SON is mainly decided by three factors: *transmission power* (PTX), *electronic power* (PTX_{elec} and PRX_{elec}) and the *node density*. We

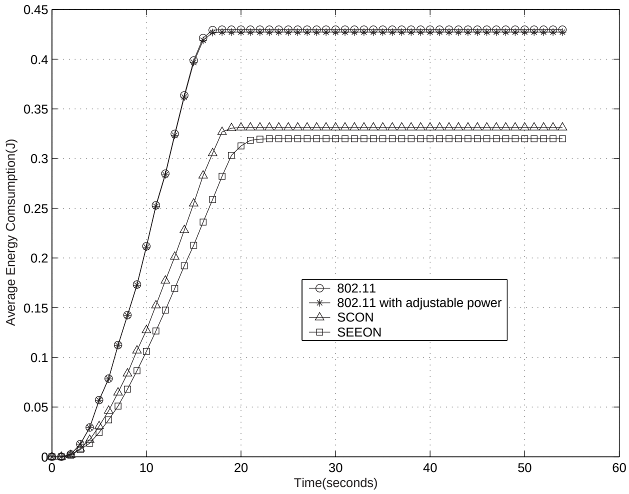

Figure 13: DSDV energy consumption

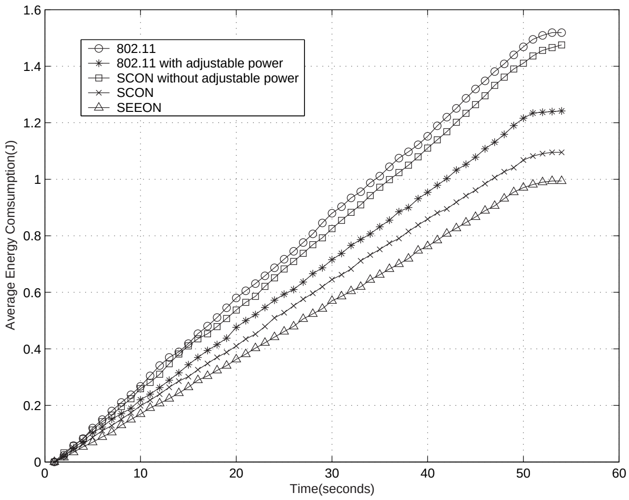

Figure 14: Energy consumption for data transmission

assume that r is the ratio of the electronic power to transmission power. Hence, we get,

$$r = PRX_{elec}/PTX \tag{13}$$

In this subsection, we investigate the relationship between the energy performance and the ratio of the electronic power to the transmission power. To evaluate this relationship, we measured the energy consumption involved in transmitting from source 73 to sink 8 with different electronic power values (2.5mW 5mW 12.5mW 25mW 50mW 125mW 250mW 500mW 1250mW). The correspondent ratios of electronic power to transmission power are 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2 and 5. The network topology and other parameters used in this section are the same as in section 3.1. In this case, the average numbers of neighbors is 13.52.

Let n denote the average number of neighbors of each node in the original 802.11 topology (i.e., before SON is executed). When $n \times r \gg 1$, the electronic energy consumption is the dominant energy consumption in the network. We can simplify equation 5 to,

$$P^{direct}(ij) \approx PTX_{elec} + PRX_{elec} \times (IN(ij) + 1) \tag{14}$$

which means the network topology after SON is mainly decided by electronic power. As aforementioned, the average number of neighbors before SON is 13.52. When $r = 1$, $r \times n = 13.52 \gg 1$. So the electronic energy consumption dominates the energy consumption and is the pivotal factor for SON.

Figure 15 shows the average number of neighbors after the pruning algorithms are executed. The number of neighbors with TOPA, SCON, SEEON increase from 3.94, 4.24, 3.56 to 13.52, 7.98, 5.78 respectively, when r increases from 0.01 to 1. When $r \geq 1$, the average numbers of neighbors with SCON and SEEON remain at the same value of 7.98 and 5.78, which means that the network topology after SON does not change further.

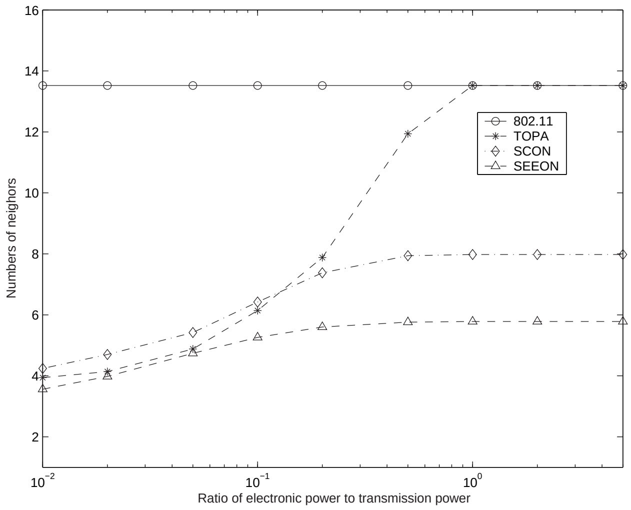

Figure 15: *Average numbers of neighbors under different r values*

Before transmitting data, we let each node exchange DSDV routing messages to construct the routing tables. To avoid the influence of the DSDV energy consumption on our evaluation of the SON, we only set the network to exchange DSDV routing messages once and keep the same routes when the packets are transmitted. Figure 16 shows overall energy consumption per node for a full process of DSDV information exchange for the whole network under different r values. When $r = 0.1$, TOPA achieves 68.7% energy savings when exchanging DSDV messages as compared to 802.11. On the other hand, SCON and SEEON consume 68.7% and 68.1% less energy than 802.11, respectively. When $r = 5$, SCON and SEEON consume 21.8% and 24.1% less energy than 802.11. However, TOPA only achieves 1.2% energy savings as compared to 802.11.

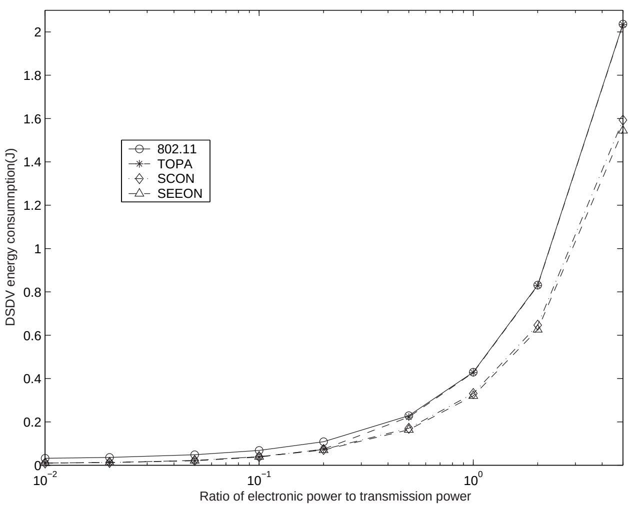

Figure 16: *DSDV energy consumption under different r values*

Figure 17 shows the average energy consumption after sending 100 packets from source 73 to sink 8 with

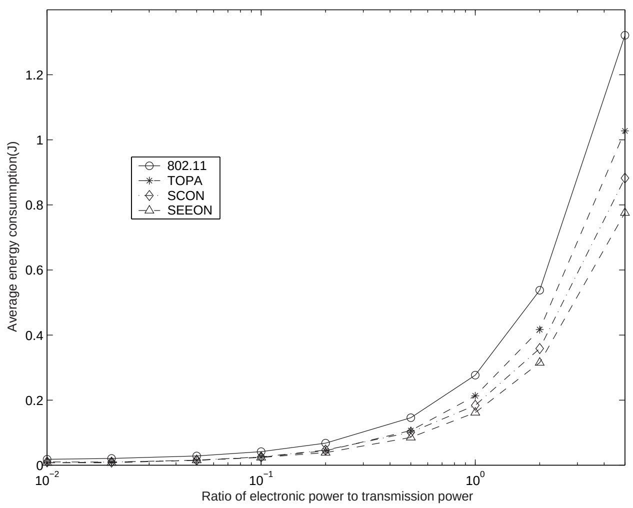

Figure 17: *Average energy consumption under different r values*

different electronic power values. When electronic power is 2.5 mW ($r = 0.01$), the energy consumption of 802.11 is 1.80e-2 J. When electronic power is 5 mW ($r = 0.02$), the total energy consumption of 802.11 is 2.06e-2 J. Note that, this results in a radio energy consumption of 1.54e-2 J. On the other hand, when electronic power is 250 mW($r = 1$), the energy consumption of 802.11 is 2.77e-1 J and the electronic energy consumption is about 2.62e-1 J. In this case, the electronic energy consumption is 16 times larger than power radio energy consumption, which means the electronic energy consumption is the dominant energy consumption if $r \geq 1$.

Assuming that the energy consumption of 802.11 is equal to 1, Figure 18 plots the energy saving rate of TOPA and SON compared with 802.11 under different r values. When $r \leq 0.1$, both TOPA and SON achieve more than 44% energy savings compare with 802.11. When $r \geq 1$, SCON and SEEON save about 33% and 41% energy. However, TOPA only saves about 22% energy. This shows that SON has a better energy performance than TOPA when electronic energy consumption is much larger than radio energy consumption.

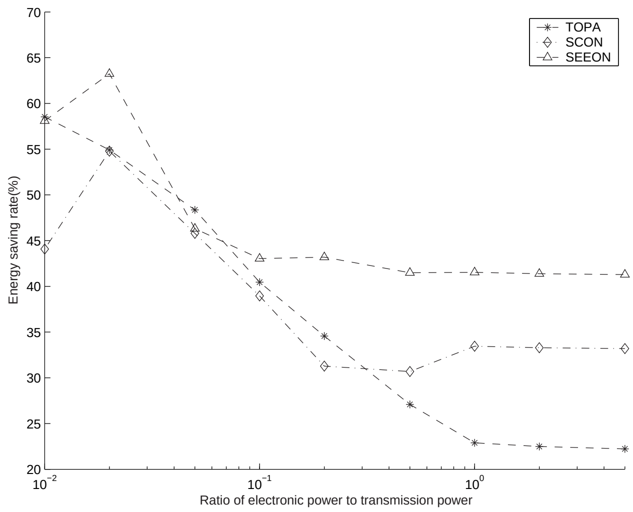

Figure 18: *Energy saving rate compared with 802.11 under different r values*

Figure 19 shows that the numbers of hops from source to sink decreases when electronic power increases. When $r \leq 1$, the routing paths may be different even with the same numbers of hops. For example, the

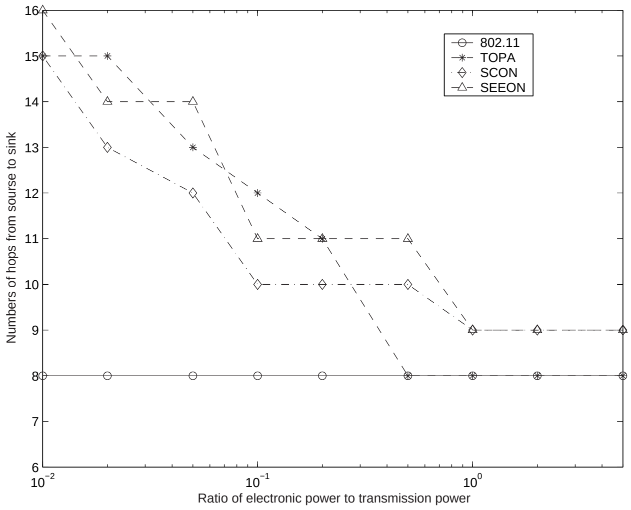

Figure 19: *Numbers of hops from source to sink under different r values*

numbers of hops with SEEON are equal to 11 when r is 0.1, 0.2 and 0.5. However, the corresponding routing paths are

```
r=0.1
Source(73)-91--62-94-13-71-75-93-4-55-Sink(8)
r=0.2
Source(73)-57--23-94-13-71-75-93-4-55-Sink(8)
r=0.5
Source(73)-57--23-94-13-71-75-93-4-77-Sink(8)
```

When $r \geq 1$, the routing path does not change further because the network topology after SON does not change.

4 Related Works

Significant research works on topology control and energy efficient protocol designs for ad hoc networks have been published in the literature. Some of them have been reviewed in section 1. Here we give a brief review for other's works.

IEEE 802.11 also specifies a power-save (PS) mode. A node can be in one of two different power modes, i.e., active mode when a node can receive packet at any time and power-save mode when a node is running at low-power state. All nodes in the network are synchronized to wake up periodically to listen to beacon message (Ad hoc Traffic Indication Message, ATIM) to decide whether to transit to active mode. Muqattash [2] *et al.* proposed a comprehensive solution for power control in mobile ad hoc networks (MANETs). Their solution emphasizes the interplay between the MAC and network layer, where the MAC layer indirectly influences the selection of next-hop by properly adjusting the power of route request packets. Jung [1] proposes an energy efficient MAC protocol for wireless LANs, where an adaptive mechanism is employed to dynamically choose a suitable ATIM window size to improve both the network throughput and energy consumptions. Hu [19] presented an efficient topology control algorithm based on Delaunay triangulation with higher throughput performance than regular-structured networks. Rodoplu and Meng [3] proposed a distributed topology control algorithm that leverages on the position information to build a topology with minimized energy consumptions. Wattenhofer [5] introduced a distributed topology control protocol based on directional information, called CBTC (Cone Based Topology Control). A set of optimizations that further reduce power consumption for CBTC is presented in [6].

One of the most exciting area of ad hoc network is the emergence of sensor networks in recent years. As sensors are normally battery power, the prime concern for sensor network is the energy efficiency and system lifetime. Most research works with the goal of increasing energy efficiency focus on turning off radios periodically [15] or use different kinds of wakeup radios [17][18]. A good survey on the topology control in wireless ad hoc and sensor networks is provided in [7]. Interested readers may refer to this paper for more reviews.

5 Concluding Remarks and Future Work

We proposed two location-aware select optimal neighbor algorithms for CSMA/CA based MAC protocol for wireless ad hoc networks. Both algorithms concentrate on the improvement of energy efficiency of the whole network through the optimization of the number of neighbors of each node.

Traditional optimum pruning algorithm (TOPA) (refer to section 1) only considers distance dependent radio transmission energy consumptions. However, the efficiency of TOPA is affected when the radio electronic energy consumptions can not be ignored compared to the radio transmission energy consumptions. Instead, our SON algorithm considers both, the radio electronic energy consumption and the radio transmission energy consumption. SON also considers the energy consumption at those irrelevant receivers in the optimized pruning process.

In this paper, NS-2 simulations show that SCON and SEEON can achieve energy savings for about 28% and 38% respectively compared with the standard 802.11 when using the the Lucent IEEE 802.11 WaveLAN card parameters. Furthermore, we have carried out extensive simulation-based evaluations of 802.11, TOPA and SON. The simulations show that the ratio between radio transmission power and radio electronic power have a significant influence on the efficiency of SON. When electronic energy consumption is a considerable part of energy consumption, SON has a better energy performance than TOPA.

An interesting area is that how the network throughput and packet latency may be influenced by the pruning algorithm. On one side, removing neighbors normally means increasing the number of hops from a specific source to a sink, thus the latency is increased. On the other side, a shorter transmission range means a smaller contenders for the channels, therefore, less contention delays and the latency is decreased. The network throughput and packet latency are also related to the traffic patterns. We would like to pursue these areas in our future work.

References

[1] E.S. Jung, *et al.*, “An Energy Efficient MAC Protocol for Wireless LANs”, In IEEE Infocom 2002.

[2] A Muqattash, *et al.*, “A Distributed Transmission Power Control Protocol for Mobile Ad Hoc Networks”, IEEE Trans. on Mobile Computing, pp.113- 128 Vol,3, Issue:2, April 2004

[3] V. Rodoplu, *et al.*, “Minimum energy mobile wireless networks”, IEEE Journal on Selected Areas in Communications, 17:1333-1344, Aug. 1999.

[4] R. Ramanathan, *et al.*, “Topology Control of Multihop Wireless Networks using Transmit Power Adjustment”, Proc. IEEE Infocom, 2000, pp.404-413.

[5] R. Wattenhofer, *et al.*, “Distributed Topology Control for Power Efficient Operation in Multihop Wireless Ad Hoc Networks”, Proc. IEEE Infocom 2001, pp. 1388-1397, April 2001.

[6] L. Li, *et al.*, “Analysis of a Cone-Based Distributed Topology Control algorithm for Wireless Multi-hop Networks”, Proc. ACM PODC 2001, pp.264-273, 2001.

[7] P. Santi, “Topology Control in Wireless Ad Hoc and Sensor Networks”, submitted to ACM Comp. Surveys.

[8] D.M. Blough, *et al.*, “The k-Neigh Protocol for Symmetric Topology Control in Ad Hoc Networks”, Proc. of IEEE MobiHoc 2003, pp.141-152.

[9] E. Shih, *et al.*, “Physical Layer Driven Protocol and Algorithm Design for Energy-Efficient Wireless Sensor Networks,” Proc. ACM MobiCom ’01, Rome, Italy, July 2001, pp. 272-86.

[10] K. Sohrabi *et al.*, “Protocols for Self-Organization of a Wireless Sensor Network,” IEEE Pers. Commun., Oct. 2000, pp. 16-27.

[11] K. Sohrabi *et al.*, “Near-Ground Wideband Channel Measurement,” IEEE Proc. VTC, New York, 1999

[12] N. Bulusu, “Self-Configuration Localization Systems,” PhD Dissertation, UCLA, 2002

[13] S. Singh, *et al.*, “PAMAS: Power Aware Multi-Access Protocol with Signalling for Ad Hoc Networks”, ACM Computer Communication Review, Vol. 28, No. 3, pp. 5-26. July 1998.

[14] W. R. Heinzelman, “Application-Specific Protocol Architecture for Wireless Networks”, PhD dissertation, MIT, June, 2000.

[15] W. Ye, *et al.*, “An Energy-Efficient MAC Protocol for Wireless Sensor Networks”, IEEE Proc. Infocom, June 2002, pp.1567-1576.

[16] M.K. Marina, *et al.*, “Routing Performance in the Presence of Unidirectional Links in Multihop Wireless Networks”, Proc. ACM MobiHoc 02, pp.12-23, 2002

[17] C. Guo, *et al.*, “Low Power Distributed MAC for Ad Hoc Sensor Radio Networks”, IEEE Proc. GlobeCom 2001, Nov. 25-29, 2001

[18] C. Schurgers, *et al.*, “Optimizing Sensor Networks in the Energy-Latency-Density Design Space”, IEEE Trans. on Mobile Computing, Vol.1, No.1, pp.70-80, January-March 2002 .

[19] L. Hu, “Topology Control for Multihop Packet Radio Networks”, IEEE Trans. on Communications, Vol.41, NO.10, pp. 1474-1481, October 1993.