International Journal of the Physical Sciences Vol. 6(7), pp. 1773-1779, 4 April, 2011
Available online at http://www.academicjournals.org/IJPS
ISSN 1992 - 1950 ©2011 Academic Journals

Full Length Research Paper

Power control in wireless ad hoc networks for energy efficient routing with end-to-end packet delay minimization

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Accepted 21 March, 2011

Wireless ad hoc networks are the networks with no infrastructure and that have limited battery. It is necessary that the nodes in the network use their energies efficiently. In this study, on-demand and position based algorithms that minimize end-to-end packet delays and that use their node energies most effectively are proposed. The proposed algorithm helps to transport packets to their destinations by keeping the data transfer power of nodes in the lowest level. The algorithm is exposed to a performance evaluation test via a simulation program that is developed in MATLAB.

Key words: Power control, wireless power, energy efficiency, routing algorithm, wireless routing, packet delay minimization.

INTRODUCTION

A mobile ad hoc network is a set of wireless nodes which cooperatively form a network without a fixed infrastructure or a centralized administration. In particular, a node communicates directly with nodes within wireless range and indirectly with all other nodes using a dynamically computed, multi-hop route via the other nodes. Nodes are free to move randomly and organize themselves arbitrarily. So, the network topology may change rapidly and unpredictably. Since nodes are usually battery operated, energy conservation is an important issue. Furthermore, because of the broadcast nature of the wireless medium, ad hoc networks are also limited by interference/capacity considerations.

There exist several studies on energy efficiency. In a study by Singh et al. (1998), five metrics related to energy were investigated and this study is one of the first works for energy-aware routing in ad hoc networks. A distributed protocol to find the minimum topology is seen in a research done by Rodoplu and Meng (1999). According to Chang and Tassiulas (2004), link costs were defined based on the energy expenditure for unit flow transmission and the initial and residual energy at the transmitting nodes. A new cost metric that is, a function of the remaining battery level and the number of neighbors of a node is used for routing. Other studies that were based on the discovery of energy efficient routes under the constraint of a fixed end-to-end bit error rate and the expected number of re-transmissions for reliable packet delivery were considered in researches by Banerjee and Missa (2002) and Manohar and Scaglione (2003). The selection of multiple energy efficient paths for a given source-destination pair were proposed by Shah and Rabaey (2002).

Transmission power control for energy efficiency has been investigated in various works. In Ramanathan and Rosales-Hain (2000) two algorithms were proposed for selecting the node transmission power.

An on-demand algorithm that aims to minimize transmission power by forwarding on the nearest neighbor node was proposed by Bae et al. (2004).

Abbreviations: AODV, Ad hoc On demand distance vector; **DIR,** Directional routing algorithm; **MFR,** most forward within radius; **PBHRA,** position based hybrid routing algorithm; **DSR,** dynamic source routing; **TORA,** temporally ordered routing algorithm; **GEDIR,** geographic distance routing.

According to Chang and Tassiulas (2000), forwarding of the packets was considered together with the power control. The authors try to increase energy consumption for the nodes having more energy and decrease it for the nodes that are poorer in terms of energy reserves. In a research done by Agarwal et al. (2001) power control was incorporated in the MAC layer by using the RTS-CTSDATA-ACK sequence to reach an agreement on the transmission power to be used while in Elbatt and Ephremides (2003) and Li and Ephremides (2007), power control, scheduling, and routing were presented together. Slow start MAC protocol was proposed by Gakamas and Varyarigos (2006). In this protocol, a slow start mechanism is used for the transmission of DATA and RTS/CTS packets to save energy and decrease interference. In addition to these ideas, a number of devices also exist and one can adjust dynamically their transmission power like the Sun SPOT device. The Sun SPOT device is a small, wireless, battery powered experimental platform that includes a range of built-in sensors (e.g., temperature sensor) and it is developed by Sun.

There are several works (Gupta and Das, 2002; Li et al., 2001; Gupta and Kumar, 2000) related to the effects of capacity and interference limitations which are necessary for maximum achievable output of an ad hoc network considering some assumptions such as network topology, the routing algorithm, and the traffic pattern. In a research by De Couto et al. (2003) the expected transmission count (ETX) metric was used, which incorporates the link loss ratios and the interference among successive links of a path. These metrics, however, ignore energy limitations, and tend to negatively impact network lifetime by overusing the energy reserves of a small set of nodes. Other works propose interference-aware routing using different definitions for the interference metric (Burkhart at al., 2004; Meyer at al., 2002). In Karagiorgas et al. (2010), the authors proposed an energy and capacity/interference-constrained algorithm.

In this study, a routing algorithm that selects a path which minimizes end-to-end packet delay and transmission power by determining possible paths from source to destination was proposed. Two different optimal energy-minimum delay algorithms were developed for position-based and on-demand algorithms.

ENERGY EFFICIENT/DELAY MINIMIZED NETWORK MODEL

The network can be shown as a weighted graph *G(V,C)* where *V* represents nodes and *C* represents the cost values between nodes. Cost value *C* can be distance for position-based algorithms and it can be signal-strength for on-demand algorithms or it can be the mixture of more than one value. For instance, a cost value may compose of distance between nodes, buffer value, and signal-strength value. The possible paths from source to destination in *G(V,C)* graph can be shown as a sub-graph $G_S(V,C)$. vector *V'* can be expressed as $V'=(V_1,V_2,\ldots,V_n)$ and vector *C'* as *C'=(c12,c13,…,c1n,c23,c24,…,c2n,…,c(n-1)n)*. Cost value is 0 for the nodes which are not in the coverage area of each other. In Figure 1, a sub-graph from node *1* to *7* is presented. c_{ij} is the cost value between node *i* and *j*. In a sample network given in Figure 1, the cost value c_{24} is 0. A link between a node and the other one that is in its coverage area is established.

In this study, it is homed to keep the total delay of the packet to be transferred under a threshold value while keeping the total energy spent from source to destination in an efficient value. So, some equations related to packet delays and energy spent by nodes are given in the following paragraphs.

Energy spent by a node for a packet is given in Equation (1).

$$E_{total} = E_a + E_t + E_r + E_c \tag{1}$$

E_a in Equation (1) refers to the energy to survive, E_t is for energy required for packet transmission, E_r for energy to retrieve a packet, and E_c is the computation energy.

$$E_t = E_{amp} \cdot d^{\alpha} \cdot b \tag{2}$$

E_t in Equation (2) is the energy sent by a node to transfer a series of bit. E_{amp} = 100 pj/bit/m^2, *d* is the distance for packet transmission, *α* is packet loss constant (2 for the paths with no interference and 4 for the paths with interference), and *b* is the number of bits (Heinzelman et al., 2000).

$$E_r = E_{elec} \cdot b \tag{3}$$

In Equation (3), the energy spent by a node to receive a packet is given E_{elec} = 50nj/bit and b is the number of bits (Heinzelman at al., 2000).

Since E_c and E_a given in Equation (1) are used as a constant value in other algorithms too, they can be neglected and the energy spent by a node to receive and transfer a packet is then approximately equal to Equation (4) (Heinzelman at al., 2000).

$$E_{total} = E_{amp} \cdot d^{\alpha} \cdot b + E_{elec} \cdot b \tag{4}$$

E_{total} depends on the 2nd or 4th root of the distance between nodes and the number of bits to be sent and retrieved.

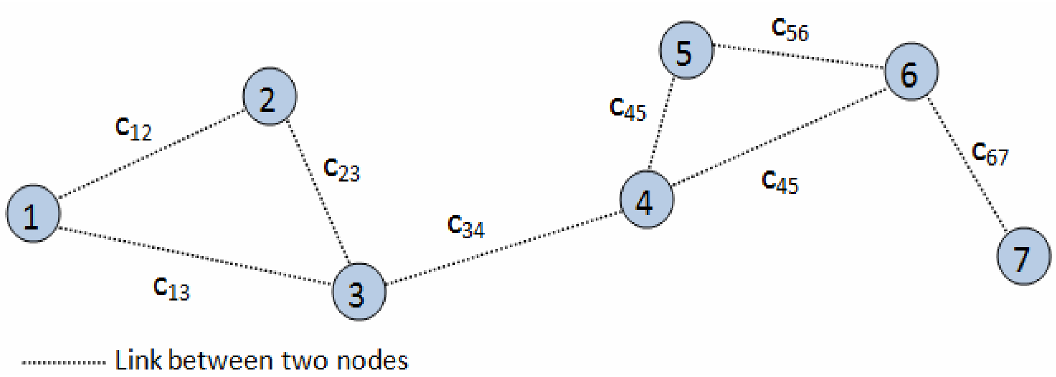


Figure 1. View of a sub-graph from node 1 to node 7.

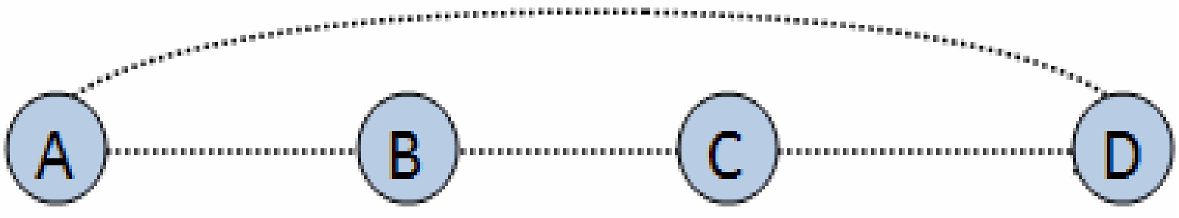


Figure 2. Comparison of packet delay and transmit power.

An expression given in Equation (5) is used to determine the packet delay from source to destination (Chen at al., 2004).

$$delay = \frac{b}{B} \tag{5}$$

According to Equation (5), *b* is the number of bits in the packet and *B* is the effective band width. The expression "*delay*" stands for the delay in one node. End-to-end packet delay depends on the number of nodes passed by the packet.

In Figure 2, nodes *B*, *C*, and *D* are in the coverage area of node *A*. Energy spent by node *A* when it sends the packet through node *B* is less than it is directly sent to *D* when Equations (4) and (5) are considered, but in the first case packet delay is three times higher. Node *A* may send the packet to *B*, *C*, and *D* by using adaptive transmission power. It is required to keep both total energy consumption and end-to-end packet delay in the effective values

The objective function for adaptive power control is given in equation (6) where E_T is the energy spent by all the nodes that are the members of the sub-graph $G_s(V',C')$ and the constraint function for keeping end-to-end packet delay in a certain threshold value is given in Equation (7).

$$E_T = \sum_{i=2}^{n} E_{t,i-1} + E_{r,i} \tag{6}$$

$$delay_T = \sum_{i=2}^{n} delay_i \tag{7}$$

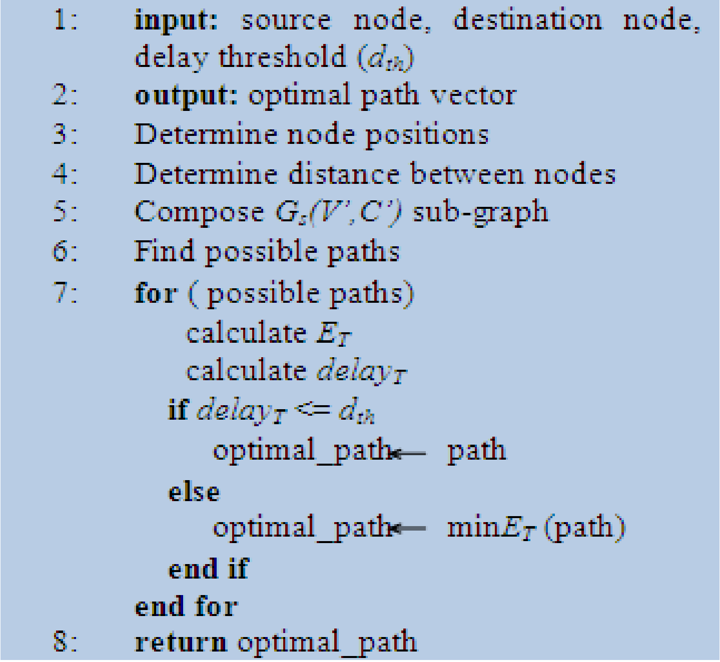
$E_{t,i-1}$: energy spent by node i-1 to send a packet, $E_{r,i}$: energy spent by node i to retrieve a packet, $delay_T$: total packet delay of all nodes in $G_S(V',C')$ sub-graph, $delay_i$: packet delay of node i.

POSITION-BASED AND ON-DEMAND ENERGY EFFICIENT/DELAY MINIMIZED ALGORITHMS

Here, the algorithm that gives a routing path to satisfy optimal energy consumption by using the objective function and the constraint are proposed.

Position-based algorithm

Position-based routing algorithms usually use localized nodes. What is meant by saying "localized" is that nodes determine their positions using Global Positioning System (GPS). PBHRA, GEDIR, DIR and MFR are that



```
input: source node, destination node, delay threshold ($d_{th}$)
output: optimal path vector
Determine node positions
Determine distance between nodes
Compose $G_s(V',C')$ sub-graph
Find possible paths
for ( possible paths)
    calculate $E_T$
    calculate $delay_T$
  if $delay_T <= d_{th}$
      optimal_path ← path
  else
      optimal_path ← min$E_T$ (path)
  end if
end for
return optimal_path
```

Figure 3. Position-based optimal path selection algorithm.

kind of algorithms in the literature (Kara et al., 2010).

The cost value *C* in graph *G(V,C)* can be the distance between nodes for that kind of algorithms. Each and every node can learn its neighbor's position via HELLO packets retrieved. So, it can easily calculate the distance using Equation (8) below.

$$d_{i,j} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2} \tag{8}$$

(x,y,z) values in Equation (8) are the values obtained from GPS and they are latitude, longitude, and altitude respectively.

The algorithm that gives optimal path is given in Figure 3.

On-demand algorithm

In case of a route requirement, on-demand algorithms start duration for route request. DSR, AODV, and TORA are examples of these types of algorithms in literature. Signal strength can be used as cost value in graph *G(V,C)*. Equation (9) is used for distance value, *d*, that is required to calculate total energy consumption in Equation (4).

$$P_r = \frac{P_t \cdot G_r \cdot G_t \cdot \lambda^2}{(4\pi)^2 \cdot d^{\alpha} \cdot L} \tag{9}$$

In Equation (9), P_r is the gathered signal strength, P_t is the sent signal strength, G_r and G_t are the acquisitions of receiver and sender antennas respectively, *d* is distance between sender and receiver, *L* is system loss, *λ* is the wavelength of the carrier signal, and *α* is path loss constant. Signal strength decreases as the distance increases since d^{α} and P_r are inversely proportional. Neighbor nodes may determine signal strength via HELLO packets they receive from each other and they may assign distance cost values.

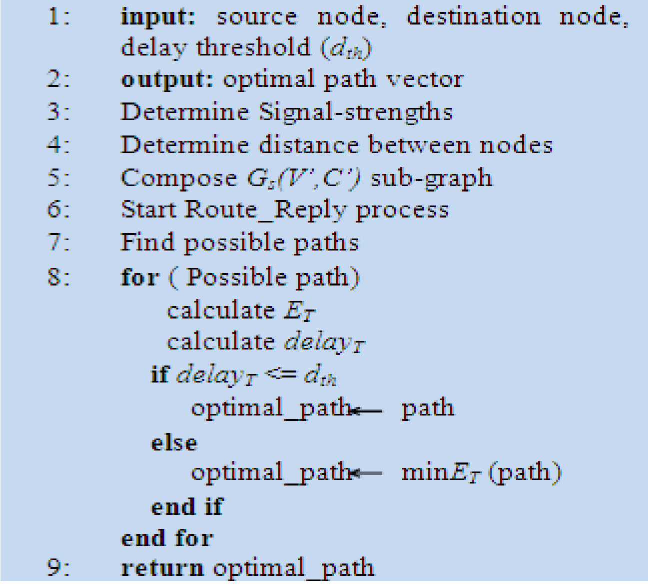
On-demand algorithms generally use source routing method after determining the route. All node addresses that includes optimal path are written to the address space of the data to be sent in source routing method.

An algorithm that gives optimal path for on-demand algorithms are given in Figure 4.

SIMULATION AND PERFORMANCE EVALUATION OF ALGORITHMS

A software is developed in MATLAB to evaluate the effects of the proposed algorithm. Simulation algorithm focuses on the analysis of packet delay and energy consumption for varying node numbers. Parameters used for simulation are the followings:

Band width used for radio device is taken as 2 Mbps. Dimension of the data packet is constant and it is 512 Byte. 5 flows of CBR traffic is generated. Numbers of



```
input: source node, destination node, delay threshold ($d_{th}$)
output: optimal path vector
Determine Signal-strengths
Determine distance between nodes
Compose $G_s(V',C')$ sub-graph
Start Route_Reply process
Find possible paths
for ( Possible path)
      calculate $E_T$
      calculate $delay_T$
    if $delay_T <= d_{th}$
        optimal_path ← path
    else
        optimal_path ← min$E_T$ (path)
    end if
end for
return optimal_path
```

Figure 4. On-demand optimal path selection algorithm.

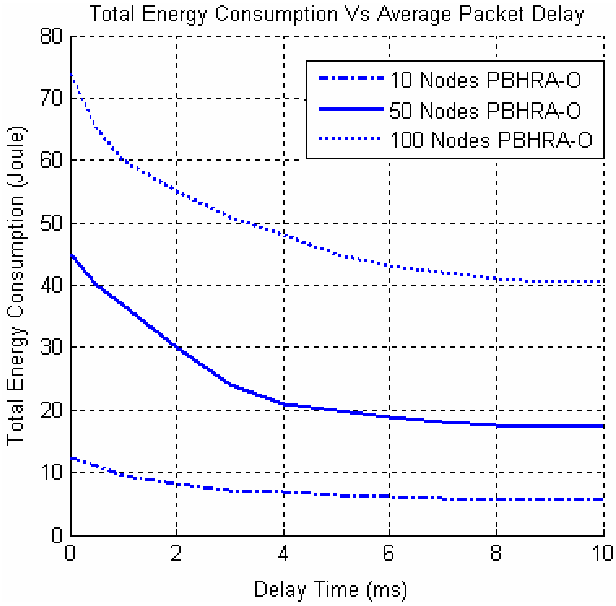


Figure 5. Energy consumption-Packet Delay graph of Optimized-PBHRA (PBHRA-O) algorithm.

nodes are taken as 10, 50, and 100 as three different values. It is assumed that the coverage area of the nodes is 100 m. Path loss constant (α) is 2.

First of all, total-energy consumption of 10, 50, and 100-noded networks against the variable d_{th} using one of the position-based algorithms, PBHRA (Kara et al., 2010), are determined. Then, optimal energy consumption values are calculated by using the optimal path algorithm we proposed.

A graphic for total energy consumption versus varying end-to-end delay time is given in Figure 5. According to Figure 5, the energy spent decreases as the delay time increases. The reason for this is that the packets that go

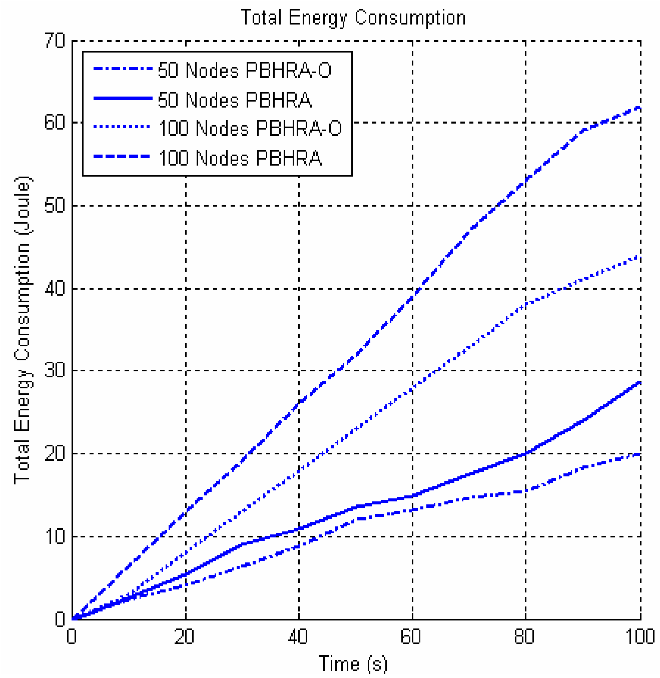


Figure 6. Energy Consumptions for Optimized-PBHRA and PBHRA with dth = 3 ms.

Table 1. Rehabilitation rates of optimized PBHRA.

Node number / Time (s)	Rehabilitation rate (%)	Node number / Time	Rehabilitation rate (%)
50/20	25.45	100/20	38.46
50/40	30	100/40	30.76
50/60	20	100/60	28.20
50/80	11.48	100/80	28.30
50/100	22.5	100/100	29.03
Average	21.99	Average	30.95

to the destination passes on more number of nodes. It is required to forward through the possible nearest node for the maximum allowed delay time to make the energy consumption less.

The proposed algorithm is compared with the current algorithm. Energy consumption measurements of 50 and 100-noded networks were done for PBHRA and PBHRA-O where simulation time is 100 s and d_{th} = 3 ms. Computation results are given in Figure 6. When Figure 6 is considered, it is clear that PBHRA consumes less power. Rehabilitation rates of the algorithm that is given in Table 1 for PBHRA are given as percentages. Rehabilitation rates of 50 and 100-noded networks are mentioned as both instant (at the end of 20, 40, 60, 80, 100 s) and average in Table 1. As it is clear from Table 1 that the proposed algorithm gives better results for the networks having plenty of nodes.

CONCLUSION

A power control method that provides long-lasting ad hoc networks that send packets to their destinations in the shortest time slice is proposed for ad hoc networks in this study. The main idea of the proposal relies on transmitting along the node in the possible nearest distance to transport the packet to its destination. Besides, it should be noted that the time it takes to reach the destination does not exceed some certain value.

As can be seen from the simulation results, the proposed algorithm optimizes energy consumption of nodes and minimizes total energy consumption. Such a network lives longer than the others.

The proposed algorithm consumes about 22% less energy for 50-noded network and 31% less for 100-noded network according to the results of the simulation. Also, it performs better for the networks with lots of nodes. This proposed algorithm gains much importance when the trend for increasing node densities in the new applications related to ad hoc and sensor networks is considered.

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