Power Control in Wireless Ad Hoc Networks for Energy Efficient Routing with Capacity Maximization

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ABSTRACT

In wireless ad hoc networks, energy-constrained operation is very important due to the limited battery capacity. One of the reasons for excessive energy expenditure in this network is irregularly distributed node patterns which impose large interference range on a certain area. In this paper, we present a simple and energy efficient on-demand routing scheme by using discrete level of power control and priority based packet scheduling. With little additional routing overhead, the proposed scheme provides better way to deliver data than existing routing protocols which use fixed transmission power.

Keywords: Wireless Ad Hoc Network, Power Control, Energy Efficient Routing, Network Capacity.

1. INTRODUCTION

The wireless ad hoc network is a candidate to satisfy the growing enthusiasm of users toward mobile computing. However, as the hosts of ad hoc network can be any type of mobile computing devices or communication tools which have limited battery capacity, energy-constrained operation usually only allows short range of radio propagation. As a way to reduce energy consumption, we are interested in the effect of power control which tunes the strength of radio transmission.

Power control approaches considered in the wireless ad hoc network can be loosely classified into two categories, power controlled topology management and power aware routing. Power controlled topology management schemes try to find lowest transmission power level for each link as far as network-wide connectivity is guaranteed. In [1], the authors propose two transmission power control algorithms to create 1-connected and 2-connected topologies. In [2], the authors propose a distributed power control algorithm based on directional information. On the other hand, power aware routing schemes try to find routes which consist of links consuming low energy. In [3], PARO, a Power-Aware Routing Optimization, is introduced. The routes are determined by the links which consume low energy. In [4], the authors conceptualize the power control problem, and provide a protocol named COMPOW. They suggest that low common transmission power maximizes throughput, extends the battery life, and reduces the contention at MAC layer. In [5], the authors propose on-demand minimum energy routing protocol using energy aware link cache based on DSR (Dynamic Source Routing) protocol [6].

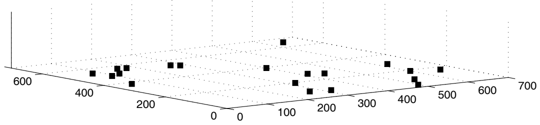
Most of approaches in these two categories present their own aspects of interest. However, those approaches usually require additional overheads. For example, some of the approaches require geographical coordinates given by GPS for the power controlled connection with nearby nodes, or additional control overheads required for actual data delivery. Also, they do not consider the distribution patterns of nodes mentioned in [7]. They assume that the nodes are randomly but uniformly distributed within the area and have same types of transceivers which have homogeneous transmission range. In this paper, we consider the effects of node distribution pattern in the wireless ad hoc network, and propose a new on-demand power aware route search scheme which provides the most transmission power efficient route within given route search delay bound. As a result, by using minimally required level of transmission power for each hop, proposed route search scheme can increase battery life of the nodes, and also increase network capacity by reducing interference range.

The rest of the paper is organized as follows. We examine the effect of node distribution patterns in Section 2. Our new on-demand power aware route search scheme is presented in Section 3. Simulation results are in Section 4. Section 5 concludes the paper.

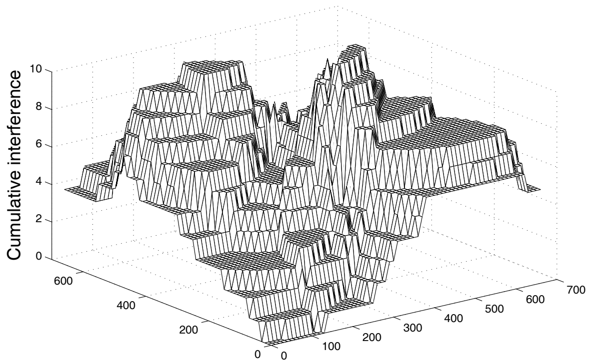
2. HANDLING IRREGULAR NODE DISTRIBUTION

In the wireless ad hoc networking environment, we can realistically assume that the network consists of different types of communication devices which use the same ISM band as a common channel. As those devices are carried and used by users, the distribution pattern of the nodes exactly reflects the movement pattern of users. Thus, devices constructing the wireless ad hoc network may have a temporal irregular distribution pattern representing their own purpose of users. Fig. 1(a) shows that a typical irregular distribution pattern composed by 20 nodes on a 670x670m area. In this case, if all the transmission powers are fixed as a certain value, the devices may suffer severe interference caused by transmissions of their neighbor devices. Fig. 1(b) shows the degree of cumulative possible interference caused by 250m transmission range of nodes. We can easily discover that the nodes located in a dense area suffer excessive interference from nearby nodes and the probability of channel acquisition is inversely proportional to the transmission range.

Thus, to flatten the degree of cumulative interference for the aforementioned network by using power control, we propose a new on-demand routing protocol with little additional control



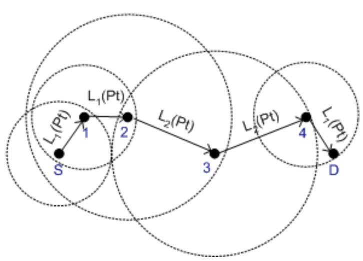
(a) Irregularly distributed nodes



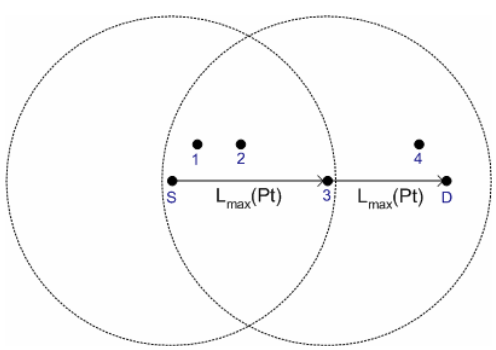
(b) Degree of cumulative interference

Fig. 1. Irregular node distribution pattern and its impact on interference

overhead. If we find a route consisted with wireless links which require minimal transmission power level, we can reduce the range of interference. As a result, we can maximize the network capacity at a given time period.



(a) Routing with power control



(b) Routing without power control

Fig. 2. Adaptive power control for network capacity

Fig. 2 shows the effect of power control. The circled areas represent transmission range for each of the senders. Without using power control, the source node S and relaying node 3 in Fig. 2(b) radiate maximum transmission power $L_{max}(Pt)$ whereas each node in Fig. 2(a) uses smaller transmission power level $L_1(Pt)$ and $L_2(Pt)$ required to connect the next node in the routing path. The difference is obvious in case when the destination is node 1. The energy efficiency comes from the following equation

$$P_r = P_t \left(\frac{\lambda}{4\pi d} \right)^n g_t g_r \qquad (1)$$

where λ is carrier wavelength, d is distance between the sender and receiver, n is path loss coefficient, and g_t and g_r are antenna gains at the sender and receiver, respectively. The value of n is typically 2 in the free space model and 4 in the two ray ground reflection model. When the threshold value of successful radio reception is given, transmission power, Pt, is related to d^n. So, small decrease of distance can save the amount of transmission power exponentially proportional to that distance.

3. ON-DEMAND POWER AWARE ROUTE SEARCH

The main components of our proposed scheme are two parts; determination of the minimum transmission power levels required to connect to nearby nodes by using less control overhead, and on-demand route discovery by using determined power levels. When the route discovery procedure is initiated by a source node, these two operations are occurred simultaneously.

Determination of Transmission Power Level

Determination of required transmission power level can be acquired by comparing the degree of power attenuation with multiple predefined threshold values required to setup transmission power level.

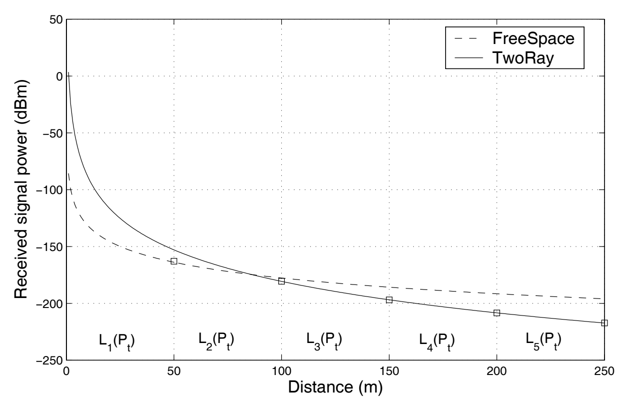


Fig. 3. Transmission power level Li(Pt) based on received signal power

Fig. 3 shows the attenuation of signal power in *dBm* scale when 914MHz Lucent WaveLAN DSSS radio interface is used. P_t is set to 0.2818W for the transmission range 250m. We use free space propagation model when the distance between the sender and the receiver is close, and two ray ground reflection model when the distance is long. The square markers on the graph represent threshold values of received signal power for the associated transmission power levels. Most of on-demand routing protocols use broadcasting schemes in their route request procedure and decide the route by using returned route reply information. We assume that the network devices in the wireless ad hoc network use a common shared channel and each of the wireless links between sender and receiver is bi-directional. We also assume that the route request packet is always sent at the highest available transmission power level to search all the possible routes.

When the route request packet is received, average received signal power is measured and compared with multiple threshold values. If the received power is less than the lowest threshold value, then we can decide that either the distance between two nodes is long or there exist obstacles degrading on-going signal. In this case, we set the required power level to $L_{max}(P_t)$. On the contrary, if the received power is greater than the highest threshold value, then we can decide that two nodes are very close and set the required power level to $L_{min}(P_t)$. The left-hand side of Fig. 4 represents the determination procedure of the required transmission power level.

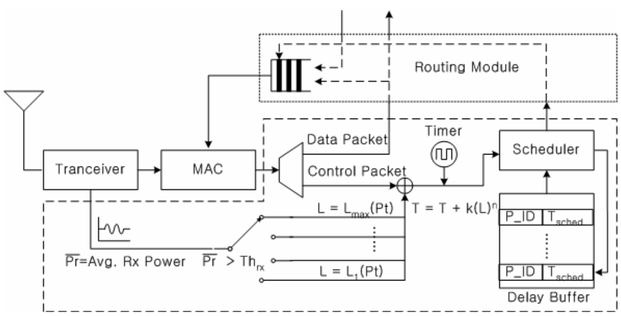


Fig. 4. The architectural model of on-demand power aware route search procedure using time-delayed control packet scheduling

On-Demand Route Discovery

For on-demand route discovery, we use basic operations of DSR for the route request and route reply procedure, although our scheme can use any type of on-demand route discovery schemes. After each of intermediate nodes determines required transmission power level for the connection with the previous sender, it records the value into the route request packet with its own ID and rebroadcasts the route request packet. To reduce the amount of unnecessary rebroadcasts, and guarantee that the packet containing the most energy efficient route arrives first at the destination, each node controls the time of rebroadcast by using a priority based packet scheduling similar to TDOR (Time Delayed On-demand Routing) [8]. TDOR uses node-based information for its packet scheduling function to lengthen network lifetime whereas our scheme uses link-based information which represents dynamic network environment.

The right-hand side of Fig. 4 depicts the procedure of priority based packet scheduling required to find an optimal route. At an intermediate node, determined transmission power level $L_i(p_t)$ is used as a basis of packet scheduling for rebroadcast. Scheduled time can be calculated by using Eq.(2)

$$T_{scheduled} = T_{now} + k\left(L_i(P_t)\right)^n \qquad (2)$$

where k is a scaling factor and n is path loss coefficient used in Eq.(1). The scheduling procedure is simple. If an arrived route request packet has the same packet ID previously broadcasted, then the scheduler drops that packet. If the calculated time is later than stored one in the delay buffer, the scheduler drops that packet, either. Only if a latterly arrived packet has sooner scheduled time than any other packet which has same packet ID, the packet can go into the delay buffer. As time goes by, a route request packet having the shortest scheduled time is selected and passed to routing module by the scheduler. In the network layer, as those control packets have higher priority than common data packet, passed route request packet is handed to MAC layer immediately, and broadcasted as soon as the channel is available. When the route request packet arrives at the destination node, the destination node calculates route reply time first and then carries out the same procedure that intermediate nodes did. The only difference is the fact that route reply packet use unicast rather than broadcast. As a result, the most transmission energy efficient route is always selected in the various node distribution patterns. Proposed approach only uses one flooding process from source to destination and always discovers the optimal route without any other computational overhead.

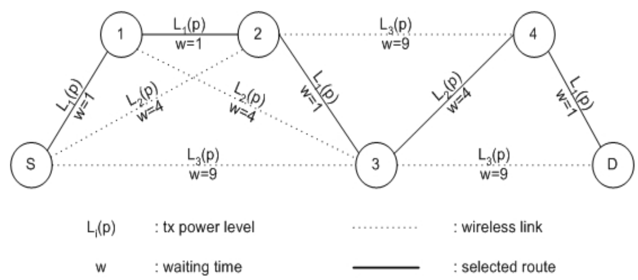


Fig. 5. Example of route discovery process

Fig. 5 illustrates simplified steps to find an energy efficient route from source node S to destination node D. The dotted line represents all possible wireless links. In this example we set the value of n, path loss coefficient, to 2. When source node S initiates route discovery process by broadcasting route discovery packet, nodes 1, 2 and 3 can receive the packet. They check the transmission power level required, add their own information to the route request packet, and put the packet into the departure queue with waiting time which has square value of transmission power level.

Node 3 waits 9 ticks before rebroadcast, where nodes 1 and 2 wait 1 tick and 4 ticks respectively. With the passage of time, each node may receive a route request packet which has already sent or scheduled in a delay buffer. As those packets are rescheduled and broadcasted only if a lately arrived one has small waiting time, we can guarantee that the route which consists of links having smallest waiting time always be constructed first. In the given example, a route request packet which has a path S-1-2-3-4 arrives first at destination node D. Now D completes the route by adding required level of transmission power for node 4 and returns route reply packet to the sender. In this time, the packet is sequentially passed to the nodes in the order specified in the route reply packet. Each relay node can use the power level specified in the route reply packet, hence reduces transmission power consumption and possible interference. We assume the existence of reliable link-level retransmission scheme to avoid unexpected loss of route reply packets. After the reply packet is arrived at the source node S, all route discovery process is done, and the source node can send the data to the destination node.

As a result, the proposed scheme can provide energy efficient routing mechanism with maximized network capacity. It allows only small portion of the area is occupied by on-going traffic, hence increases spatial reusability. Our scheme can be used either for one-hop communication in sparsely located area, or for multi-hop communication in densely located environment without using external source of information for overall network connectivity.

4. SIMULATION AND EVALUATION

To verify the effect of our scheme, the simulation is performed with ns2 [9] network simulator. In our simulation, we investigate the network capacity as well as transmission energy consumption. We assume the IEEE 802.11 Wireless-LAN as the radio device which has 2Mbps bandwidth. The data packets are assumed to have a fixed size of 512byte. We generate 5 flows of CBR traffic for each of our simulations.

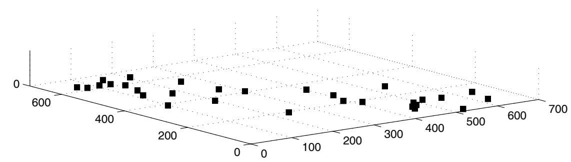
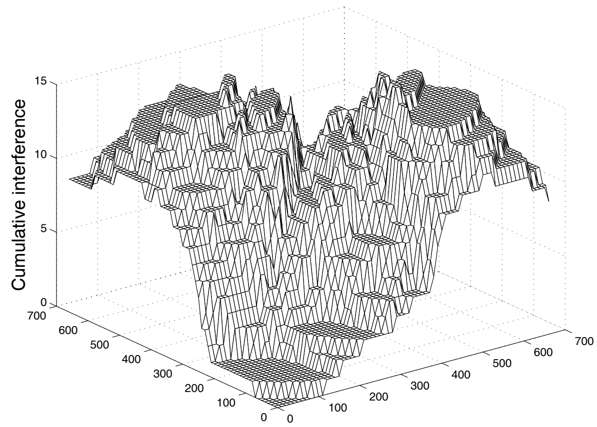


Fig. 6. Node distribution pattern: 30 nodes in 670x670m^2 area

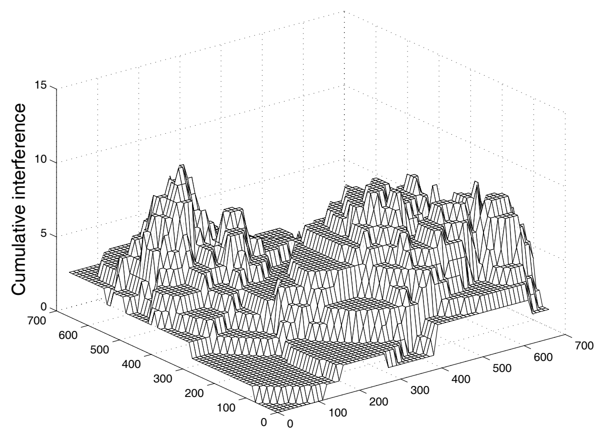
Our simulation consists of two parts. First, we evaluate our on-demand power aware route search scheme with 30 nodes irregularly distributed in the 670x670m^2 area. The distribution pattern is shown in Fig. 6. We do not consider mobility model in this simulation because the purpose of this simulation is to verify the characteristics of routes discovered by using on-demand power aware route search.

Fig. 7 demonstrates the effect of low power transmission acquired by on-demand power aware route search scheme. To observe the impact of power control on the network capacity, we count the number of transmissions which can be simultaneously occurred and affect to each other at a given time slot. Entire area is divided by 10x10m^2 size small cell. The height of each point in Fig. 7(a) and Fig. 7(b) represents cumulative interference caused by nodes' average transmission power level.

Fig. 7(a) depicts the network using fixed 250m transmission range whereas Fig. 7(b) depicts the same network using 5 different transmission range varied from 50m to 250m. In Fig. 7(a), the highest interference value is 18 and average value is 9.1 whereas in Fig. 7(b) the values are 9 and 2.6 respectively. Based on this result, we can conclude that transmission power control based on on-demand power aware route search scheme can reduce average interference more than half when the nodes have same probability of transmission at a given time. In [10], Gupta and Kumar estimate that if node density is constant, the total one-hop capacity is $O(n)$ and the total end-to-end capacity is roughly $O(n/\sqrt{n})$. Although we use a fixed number of nodes within bounded area in this simulation, the result of decreased interference can provide the same effects to increase nodes without increasing node density, thus can increase the network capacity.



(a) Cumulative interference caused by fixed transmission power



(b) Cumulative interference using power aware route search

Fig. 7. Effect of low power transmission on network capacity

In the second part of our simulation, we use randomly distributed node set with mobility generated from random waypoint model. To reflect the effect of network density, the number of nodes in each node set varies from 10 to 50 in the 670x670m^2 fixed area. We assume that the speed of nodes may not exceed the speed of pedestrians and set the maximum speed of nodes to 1m/sec. We use 5 flows randomly generated CBR traffic with sending rate of 4 packets per second. Each simulation runs for 100 seconds. The purpose of this simulation is to evaluate the degree of energy saved at various network conditions. The results are compared with DSR.

Fig. 8 shows the number of packets transmitted by source nodes who originate the CBR traffic and intermediate nodes who relay packets to the destination nodes. The number of packets which are transmitted by source nodes increases along with increasing network density. However, when the nodes are more than 40, there is no more increase in sending rate because the number of nodes required to connect all the others within bounded area is already satisfied. The number of forwarded packets in DSR is almost fixed when the nodes are more than 20. This is because the hop count of end-to-end packet delivery may not exceed 2 when using fixed 250m transmission range. On the other hand, our on-demand power-aware route search scheme (PARS) shows continuous increase of forwarded packets. This result exactly represents characteristics of proposed scheme which prefers short distance data transmission to long distance one.

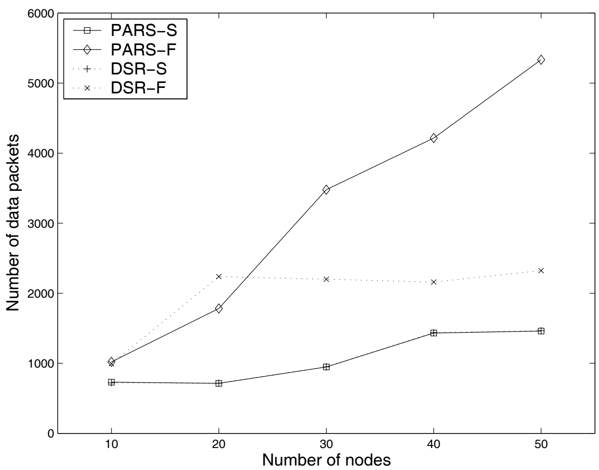


Fig. 8. Packets transmitted by source and intermediate nodes. S represents packet sent by source nodes and F represents packet forwarded by intermediate relaying nodes.

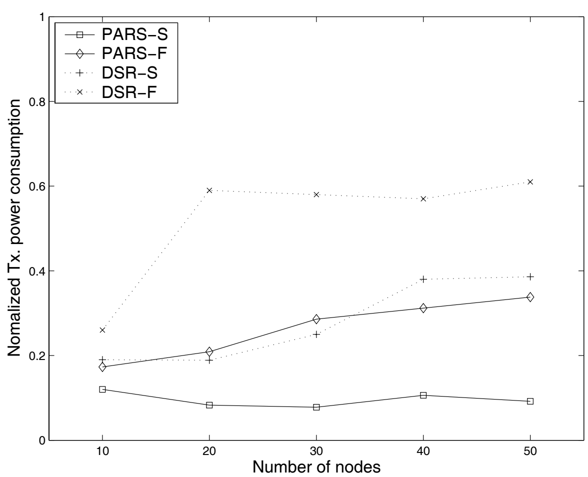


Fig. 9. Normalized transmission power consumption

In Fig. 9, we can observe the effect of power saving acquired by using proposed scheme. Each point of value represents normalized power consumption. The values are divided by total transmission power consumed in DSR with 50 nodes. Power consumption patterns of sending and forwarding operation in DSR reflect the number of packets transmitted since we use fixed transmission power in DSR. On the other hand, the power consumption pattern of proposed scheme shows continuous decrease even when the network is dense enough. As P_t is relative to d^n in Eq.(1), linear increase of the number of intermediate hops can not affect the exponential decrease of power consumption until all the nodes can communicate with minimum level of transmission power, $L_{min}(P_t)$. The simulation result shows that regardless of network density, proposed scheme can achieve more than 50% of power saving in transmission power consumption.

5. CONCLUSION

This paper proposes an on-demand power controlled routing scheme for energy efficient operation and capacity maximization in wireless ad hoc network. The proposed scheme shows simple and energy efficient route discovery procedure. The simplicity of our scheme comes from the fact that route selection process is embedded in the distributed packet scheduling based on transmission power level. Also, the energy efficiency comes from data delivery process by using minimal discrete level of transmission power. As a result, the proposed scheme can alleviate cumulative interference problem in a dense area by reducing transmission power range. Without using external source of information or collecting network-wide information in a proactive manner, the proposed scheme provides better way to deliver data than other routing protocols which use fixed transmission power.

6. ACKNOWLEDGMENTS

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