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PARO: A Power-Aware Routing Optimization Scheme for Mobile Ad hoc Networks

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Abstract

Due to fact that mobile ad hoc nodes have a critical need to preserve battery power, MANET routing protocols need to consider power saving techniques during operations. In this Internet-Draft we discuss PARO, a Power-Aware Routing Optimization protocol that minimizes the transmission power necessary to forward packets between wireless devices. Using PARO, intermediate nodes can forward packets between source-destination pairs thus reducing the aggregate transmission power consumed by wireless devices. An important property of PARO is that it outperforms traditional broadcast-based routing protocols due to its power efficient point-to-point on-demand nature. The protocol is designed to operate as a stand-alone multihop routing protocol for local-area wireless networks (e.g., single-hop home networks, single-hop sensor networks, WLANs, etc.) and as a power-aware enhancement for routing in wide-area MANETs.

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1. Introduction

Transmission power control used for communications impacts the operational lifetime of devices in different ways depending on the average transmission power consumption compared to the total average power consumption of a device. For devices where transmission power accounts for only a small percentage of the overall power consumed (e.g., a wireless LAN radio attached to a notebook computer) reducing or increasing the transmission power may not significantly impact the device's operational lifetime. In contrast, for small computing/communication devices with built-in/attached radios (e.g., cellular phones, PDAs, etc.) reducing transmission power may extend the operational lifetime of a device significantly, thus, enhancing the overall user experience.

This memo specifies PARO, a power-aware routing optimization protocol for wireless networks where all nodes are located within the maximum transmission range of each other. PARO can also perform power optimization as a layer 2.5 routing scheme operating below traditional layer 3 wide-area ad-hoc routing protocols. PARO uses packet forwarding as a way to reduce the transmission power necessary to deliver packets in the network, thus increasing the operational lifetime of networked devices.

1.1. Applicability

PARO is applicable to wireless networks where all nodes are located within transmission range of each other. To provide out-of-range power-aware routing support, a layer 3 ad-hoc routing protocol (e.g., MANET routing protocol) should be used above PARO.

1.2. Terminology

node
A node with wireless transceiver.

forwarding node
A node forwarding packets between two other nodes.

source node
A node generating and transmitting data packets to another node.

control packet
route-redirect and route-maintenance packet.

data packet
An IP packet that is not a control packet.

route-redirect packet
A control packet transmitted by a potential forwarding node to inform another node about the existence of a better power-aware route.

route-maintenance packet
A control packet transmitted by source nodes in order to maintain a route.

route-maintenance frequency
Rate of route-maintenance packets per second necessary to maintain a route.

redirect timeout
Validity time of mappings in Redirect table.

overhear timeout
Validity time of mappings in Overhear table.

1.3 Motivation

Typically, more power is consumed during the transmission of packets than their reception or during ''listening'' periods. Transmission to a distant device at higher power levels may consume a disproportionate amount of power in comparison to transmission to a node in closer proximity. Figure 1 shows an example of a network composed of three nodes located within transmission range of each other. In this case, nodes A and B use node C to forward packets to each other. The fact is that packet forwarding can significantly reduce the transmission power necessary to deliver packets between A and B nodes when node C is located near the mid point, between nodes A and B. More than one forwarding node can be added between source-destination nodes resulting in even lower aggregate transmission power.

```
O <-------------------> O <--------------------> O
A                       C                        B
```

Figure 1. Example of packet forwarding

In PARO, we propose that intermediate nodes forward packets between source and destination pairs even if source-destination pairs are located within direct transmission range of each other. This operation requires that radios are capable of adjusting transmission power on a per-packet basis. A consequence of this approach is that traditional single-hop networks (e.g., local area networks) can be considered as multi-hop networks requiring routing protocols (similar to that found in traditional wide-area ad-hoc networks) for data forwarding.

One common property of most wide-area routing protocols [1] [2] [3] is that they discover routes using different versions of ''flooding-broadcast protocols'' by transmitting with maximum power in order to minimize the number of forwarding nodes between any source-destination pair. MANET routing protocols are based on this principle and attempt to minimize the number of hops between source-destination pairs. A good broadcast flooding algorithm is crucial to the operation of any wide-area routing protocol to ensure all nodes maintain identical routing databases. Delivering data packets in a wireless network using a traditional ''minimum-hop route'', however, require more transmission power to reach the destination compared to an alternative approach that uses more intermediate nodes.

Increasing the number of intermediate hops can be achieved by reducing the transmission range used to discover routes in the network. Reducing the transmission range, however, has the effect of increasing the number of signaling packets transmitted. However, a linear decrease in transmission power generates an exponential increase of the number of signaling packets transmitted to completely flood the network. In addition, it is not possible to arbitrarily reduce the transmission power to any value, thus potentially maximizing the number of forwarding nodes between source destination pairs. Rather, there is a limitation on the lower bound of transmission power needed to completely flood routing information in the network that depends on the density distribution of nodes in the network. This limitation restricts nodes discovering some routes to other nodes if they use a transmission power smaller than the "critical transmission power". Signaling packets transmitted using less power than the critical transmission power are likely to get lost rather than reaching the final destination node.

Due to these challenges, wide-area routing approaches based on broadcast flooding techniques are either inefficient (e.g., they generate too many signaling packets for low broadcast transmission power) or incapable of discovering routes that ''maximize'' the number of intermediate forwarding nodes between source-destination nodes, thus minimizing transmission power. The existing MANET routing protocols are designed to use flooding techniques at maximum power to discover routes. In addition, these protocols are optimized to ''minimize'' the number of hops between source-destination pairs so as to promote minimum end-to-end delay. Because of these characteristics (i.e., flooding using maximum power and maximizing the number of hops), MANET routing protocols may not provide a suitable foundation for power-aware routing in ad-hoc networks. As a result, there is a need to develop new power-aware routing approaches.

1.4. Protocol Overview

The design of a power-efficient routing protocol should consider both data transmission and route discovery. In terms of power transmission, these protocols should be capable of efficiently discovering routes involving multiple hops, thus minimizing the transmission power in comparison to standard flooding-based ad-hoc routing designs. PARO departs from traditional broadcast-based design, and supports a node-to-node based routing approach that is more suited to efficiently discovering power-aware routes in wireless ad-hoc networks. In what follows, we provide an overview of PARO and address link assumptions, routing policy, cost function and protocol operations.

2. Design Consideration

2.1 Link Assumptions

PARO requires that radios are capable of dynamically adjusting the transmission power used to communicate with other nodes. Commercial radios including IEEE 802.11 and Bluetooth include a provision for power control. PARO assumes that the transmission power required to transmit a packet between node A and B is somewhat similar to the transmission power between node B and A. This assumption may be reasonable only if the interference/fading conditions in both directions are similar in space and time which is not always the case. Because of this constraint PARO requires an interference-free Media Access Control (MAC) found in frequency band radios such as Channel Sense Multiple Access (CSMA). CSMA standards use collision avoidance techniques (RTS-CTS) to make sure only one node transmits data packets at a time, thus minimizing the interference caused by simultaneous transmissions.

PARO requires source and destination nodes be located within the maximum transmission range of each other. This limitation suggests that PARO can inter-operate with traditional layer 3 ad-hoc routing protocols to provide energy-efficient routes in topologies where source and destination nodes are outside the maximum transmission range of each other and layer 3 packet forwarding becomes necessary. PARO requires that every data packet successfully received is acknowledged at the link layer and that the nodes in the network are capable of overhearing any transmissions by other nodes as long as the received signal to noise ratio (SNR) is above a certain minimum value. Any node should be capable of measuring the received SNR of overheard packets. This includes listening to any broadcast, unicast and control (e.g., acknowledgment) packets.

2.2 Policy

In PARO we focus on a policy that minimizes transmission power in the network only. An alternative policy could attempt to balance the power in the network (e.g., battery level). Policies that minimize and balance power could be orthogonal to each other. Choosing a route that balances power may not minimize transmission power, however. As a result, inefficient use of power resources could take place thus limiting the availability of power reserves in future. While balancing the power reserves in the network is a desirable property of a routing protocol, we have yet to consider this in our work.

2.3 Cost function

In PARO the cost of a directional link connecting node A with node B is defined by the minimum transmission power, Tmin(A,B), at node A such that the receiver at node B is still able to receive the packet correctly. In a network with several alternative routes between a given source-destination pair, the cost of each alternative route is the sum of the minimum transmission power of each link along the route. We consider transmission power only, thus, it neglects the cost of processing overheard packets and the cost of keeping the radio in a listening mode.

PARO tries to find the route for which the aggregate transmission power is minimized, and furthermore, it tries to discover this route using as little transmission power as possible (e.g., the power consumed by signaling packets). PARO accommodates both static and mobile environments. For the case of static networks, once a route has been found there is no need for route maintenance unless some nodes are turned on or off. In a static network, transmitting a large amount of data traffic clearly outweighs the cost of finding the best power-efficient route. In this case, we may not need to be as efficient while discovering such a route. In mobile environments, however, there is a need for route maintenance, which may outweigh the cost of data transmission in some cases.

3 Protocol Details

3.1 The PARO Model

In PARO nodes operate in promiscuous mode and are capable of overhearing packets transmitted by other nodes as long as their received power is above a certain capture threshold. Prior to transmitting a packet, a node updates the packet's header to indicate the power used for its transmission. A node overhearing another node's transmission can then use this state information plus a localized measure of the received power to compute, using a propagation model, the minimum transmission power necessary to reach the transmitting node. In this simple manner nodes learn the minimum transmission power toward neighboring nodes. PARO does not, however, maintain routes to other nodes in the network in advance but discover routes on a per-node on-demand basis. This approach has the advantage that signaling packets, if any, are transmitted only when an unknown route to another node is required prior to data transmission, thus reducing the overall power consumption in the network.

At first the operation of PARO may seem counter-intuitive because in the first iteration of PARO the source node communicates with the destination node directly without involving any packet forwarding by intermediate nodes. Any node capable of overhearing both source and destination nodes can compute whether packet forwarding can reduce the transmission power in comparison to the original exchange between source and destination nodes. When this is the case an intermediate node may send a "route-redirect" message to the source and destination nodes to inform them about the existence of a more power efficient route to communicate with each other. This optimization can also be applied to any pair of communicating nodes, thus more forwarding nodes are added to a route after each iteration of PARO reducing the end-to-end transmission power. PARO requires several iterations to converge toward a route that achieves the minimum transmission power.

The PARO model includes three main algorithm modules for overhearing, redirecting and route-maintenance, as shown in Figure 2. The overhearing algorithm receives packets overheard by the MAC and creates information about the current range of neighbor nodes. Overheard packets are then passed to the redirecting module which computes if route optimization through the intermediate node results in power savings. If this is the case, the redirect module transmits route-redirect messages to the nodes involved (e.g., source and destination nodes) and creates appropriate entries in the redirect table. The overheard packet is then processed by the packet classifier module which passes the packet to the higher layers if both MAC and IP addresses match, drops the packet if neither MAC nor IP addresses match or forwards the packet to another node when only the MAC address matches. In the later case, PARO searches the redirect table to find the next node in the route for the packet and then searches the overhear table to adjust the transmission power to reach the next node en-route.

```
                L3 and Higher layers
                      ^                   |
                      |                   V
- - - - - - - - - - - - - - - - - - - - - - -- - - - -
                      |                   |
                      |             -------------------
                      | MAC&IP      |route-maintenance|
         packet   *|--|             -------------------
     classifier  * |       MAC                | source nodes
       -------->*  |-------------------|  | only
       |         * |---                |  |
       |          *|  |                |  |
       |              V sink           |  |
       |                               |  |
       |            route-redirect     |  |
       |      -----------------------  |  |
       |      |                     |  |  |  DLC
     -------------    |Redirect| <--|--|--*
     |Redirecting|--> | table  | <--|--*  |
     -------------    |        |    |  |  |
       ^                            |  |  |
       |                            |  |  |
       |                            |  |  |
     ------------     |Overhear| <--|--|--*
     |Overhearing|--> | table  | <--|--*  |
     ------------     |        | <--*  |  |
       ^                            |  |  |
       |                            |  |  |
- - - - - - - - - - - - - - - - - - - - - - - - - -
       |              MAC           |  |  |
       |                            V  V  V
- - - - - - - - - - - - - - - - - - - - - - - - - -
                         PHY
```

Figure 2. The PARO Model

When PARO receives a data packet from the higher layers it searches the redirect table to see if a route toward the destination node exists. If this is not the case, PARO searches the overhear table to see if transmission power information regarding the destination node is available. If this is not the case, PARO transmits the packet using maximum transmission power anticipating that the receiving node is located somewhere in the neighborhood. Once the destination node replies with a packet of its own then PARO's route optimization follows as described previously.

PARO relies on data packets as the main source of routing information in the network. When nodes are mobile and no data packets are available for transmission, a source node may be required to transmit explicit signaling packets to maintain a route. The role of the route maintenance algorithm is to make sure a minimum flow of packets is transmitted at all in order to maintain the route when no data packets are available at the source node.

3.2 PARO Functions

In this section, we briefly describe the overhearing, redirecting and route-maintenance algorithms that operate in both static and mobile networks.

3.2.1 Overhearing

The overhear algorithm processes packets successfully received by the MAC and creates (or refreshes an entry if information associated with the overheard node already exists) a cache entry in the overhear table. This cache entry contains the triple [ID,time,Tmin], where the ID is a unique identifier of the overheard node (e.g., MAC or IP address), time is the time at which the overheard event occurred and Tmin is the minimum transmission power necessary to communicate with the overheard node.

Using a propagation model that takes into account the transmitted power, overheard power and node sensitivity it is possible to compute the minimum transmission power Tmin between the transmitting and overhearing nodes. Because of fading and other channel impairments it is not recommended to compute the minimum transmission power using one overheard packet only. A better approximation is to take a moving worst-case approach, where the overhear node buffers up to M previous measurements of the minimum transmission power and then chooses the one with the highest value.

Any node transmitting a packet to the next hop in the route has to determine the next hop's current range, which may be different from its last recorded position. Clearly, the preferable transmission estimate is the one that transmits a packet using minimum transmission range. In PARO, we address this issue by transmitting a packet with an extra "delta" transmission range than previously recorded, thus increasing the probability of reaching the next hop node with the first attempt. Thus delta represents how much the transmitting node over estimates the transmission range of the next node en-route. The value of delta depends on the average speed of nodes and the time interval between the last time the next node en-route was overheard and the current time; we refer to this interval as the "silence-interval". The longer the silence-interval the greater the uncertainty about the current range of the next node en route and therefore the larger the value of delta. We resolve this problem by requiring source nodes to transmit route-maintenance packets toward destination nodes whenever no data packets are available for transmission for a specific interval called route-timeout. Transmission of route-maintenance messages only occur whenever a node that is actively communicating with another node stops transmitting data messages for a route-timeout interval. The transmission of route-maintenance messages put an upper bound on the silence-interval, thus, an upper bound on delta. The route maintenance message contains no extra information beyond the destination node and transmission power fields, thus it adds little overhead.

3.2.2 Redirecting

The redirect algorithm is responsible for performing the route optimization that leads toward discovering routes requiring less transmission power. This module performs two basic operations: compute-redirect, which computes whether a route optimization between two nodes is feasible; and transmit-redirect, which determines when to transmit route-redirect messages.

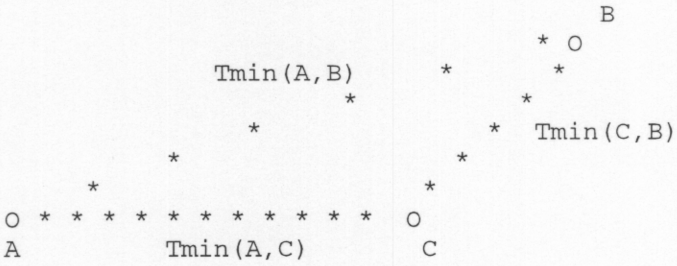

Figure 3. route-redirect

3.2.2.1 Compute Redirect

Figure 3 illustrates how compute-redirect operates. In this example nodes A, B and C are located within maximum transmission range from each other and, initially, node A is communicates directly with node B. Because node C is capable of overhearing packets from both A and B nodes, it can compute whether the new route A<->C<->B has a lower transmission power than the original route A<->B. More precisely, node C computes that a route optimization between nodes A and B is feasible if:

Tmin(A,B) > alpha (Tmin(C,A) + Tmin(C,B))   [1]

Similarly, we define the optimization percentage of adding a node between two other nodes in a route, Opt, as:

Opt = (Tmin(C,A) + Tmin(C,B)) / (Tmin(A,B) [2]

The factor alpha in Equation 1 above, restricts the area between two nodes where a potential forwarding node is allowed to transmit route-redirect messages. For networks where nodes are static and saving battery power is important (e.g., a sensor network) alpha can be set around 1.1-1.2, meaning that even a small improvement in transmission power is worth the drawback of adding an extra node (e.g., hop) to the route. Once a node computes that route optimization is feasible, it creates an entry in its redirect table. Because of mobility, a forwarding node may move to a location where it no longer helps to optimize the transmission power between two nodes. In this case, it is necessary to remove such a node from the path using another route-redirect message.

3.2.2.2 Transmit Redirect

In PARO, several nodes may simultaneously attempt to transmit route-redirect messages to one node. Because only one intermediate node between two nodes is added at a time, any route-redirect message except the one transmitted by the node computing the lowest Opt percentage represents wasted bandwidth and power resources. For sparsely populated networks, this may not be a problem. However, this is clearly an issue for densely populated networks where several route-redirect messages would be anticipated. The transmit-redirect procedure addresses this issue by giving priority to transmit a route-redirect message to intermediate nodes computing lower route optimization values first. In this manner, a potential forwarding node overhearing a route-redirect advertisement from another node offering a route-redirect with a lower Opt value would refrain from transmitting its own route-redirect request

There are several ways to give preferential access to certain messages in a distributed manner. We used a simple approach which consists of applying a different time-window before transmitting the route-redirect message after the triggering event takes place (e.g., the lower the Opt value computed, the shorter the intermediate node waits to transmit its route-redirect request). The actual lower and upper bound of the waiting interval are set such that they do not interfere with predefined timers used by the MAC protocol, making these bounds MAC dependent.

In the unlikely scenario that more than one route-redirect request is transmitted, the target node will choose the one providing a lower Opt value. After receiving a route-redirect message, a node modifies its own redirect-table putting the source of the redirect message as the next hop in the route for the specific source-destination route.

3.2.3 Route-Maintenance

In static networks no route maintenance is required once the initial route between source and destinations nodes has been found other than when nodes are turned on or off. PARO relies on data packets as the main source of routing information. In the case of mobile nodes, data traffic alone may not be sufficient to maintain routes. Consider the extreme case of a source node transmitting packets once every second to a destination where every node moves at 10 meters/second on average. In this example information about the range of the next node en route would be outdated as a basis for the transmission of the next packet. Depending on node density and mobility there is a need to maintain a minimum rate of packets between source and destination pairs in order to discover and maintain routes as forwarding nodes move in and out of existing routes. In PARO a source node transmits route-maintenance packets when there are no data packets available to be sent within a route-timeout interval.

3.3 Packet Formats

3.3.1 Data packet

A PARO data packet is a standard IP packet with a new IP option containing power related information.

Currently the following type of control information is defined in the PARO IP option (details are for further study):

Transmission power	Transmission power used to transmit route-redirect packet.

3.3.2 Route-Redirect packet

A route-redirect packet is an ICMP packet of which

- the source address is the IP address of the sending node
- the destination address is the destination node of the route-redirect message
- the type is PARO control packet and the code is route-redirect

The payload of the route-redirect packet carries transmission power related information in the following format

```
 0                   1                   2
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-     -+-+-+-+-+-+-+-+-
|     Type      |    length     | Data...      | Type ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-     -+-+-+-+-+-+-+-+-
```

Type	Indicates the particular type of control information.
Length	Indicates the length (in bytes) of the following data

field within. The length does not include the Type and Length bytes.

Data	This field may be zero or more bytes in length. The meaning, format and length of the data field is determined by the Type and Length fields.

Currently the following type of control information is defined (details are for further study):

Route source
IP address of source node.

Route destination
IP address of destination node

Optimization percentage (Opt)
Ratio of optimized route with original route (see Section 3.2.1.1).

Transmission power
Transmission power used to transmit route-redirect packet.

3.3.3 Route-Maintenance packet

A route-maintenance packet is an ICMP packet of which

- the source address is the IP address of the source node
- the destination address is the final destination node of the route
- the type is PARO control packet and the code is route-maintenance

The payload of the route-maintenance packet carries transmission power related information in the following format

```
 0                   1                   2
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-     -+-+-+-+-+-+-+-+-
|     Type       |    length      | Data...       | Type ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-     -+-+-+-+-+-+-+-+-
```

Type	Indicates the particular type of control information.
Length	Indicates the length (in bytes) of the following data field within. The length does not include the Type and Length bytes.
Data	This field may be zero or more bytes in length. The meaning, format and length of the data field is determined by the Type and Length fields.

Currently the following type of control information is defined (details are for further study):

Packet Counter
Used to let intermediate nodes in the route detect missing packets.

Transmission power
Transmission power used to transmit route-redirect packet.

3.4 State Tables

3.4.2 Overhear Table Format

An entry in the overhear table contain the following fields:

- Timestamp

- IP address of the overheard node

- Minimum transmission power to reach the overheard node

3.4.1 Redirect Table Format

An entry in the overhear table contain the following fields:

- Timestamp

- IP address of the source node of the route

- IP address of the destination node of the route

- IP address of next node en-route

- IP address of previous node en-route

4 Security Considerations

Currently, PARO does not specify any special security measures. This internet-draft assumes that all nodes participating in the PARO protocol do so without malicious intent to modify or corrupt packet information as well as the ability of the network to route packets. Nodes participating in PARO benefit from the relay capability of other nodes that motivates their participation in the protocol. Encryption techniques can be used in the air interface to prevent attack by outsiders.

Acknowledgments

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