A Power-Aware Routing Algorithm*

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Abstract

Communication-related operations are a major source of energy consumption in mobile nodes. In particular, consumption is significantly high when ad hoc routing is employed as nodes are assigned additional operations to support the routing of packets from other nodes. This research extends the cognitive packet networks initiative to support routing of packets in wireless, mobile ad hoc networks. We explore the use of *smart packets* to enable a power management scheme, which can be directly integrated into the routing algorithm. Our *ad hoc cognitive packet networks* proposal constructs an intelligent environment on which smart packets acquire information and learn how to make routing decisions. These decisions are made from the available knowledge and extend the working lifetime of mobile nodes. Additionally, we report on a simulation study that indicates the robustness of this routing solution in seeking fast, energy efficient routes.

1 INTRODUCTION

Ad hoc networks are characterized by unpredictable topologies, which impede the use of routing algorithms originally designed to operate over semi-static, wired networks. The topological dynamism of ad hoc networks is the result of node mobility, the presence of wireless links (which introduce high error ratios), and unreliable nodes (because of their limited resources). In a typical wireless system, a major factor that restrict the reliability of nodes is the limited battery energy that they can carry. These factors add together to create a highly error-prone network environment on which routing algorithms operate to establish adequate paths.

Cognitive packet networks offer fast, adaptive routing, which make them particularly attractive to ad hoc situations. Smart packets can be custom tailored to seek minimization of factors that produce errors within ad hoc networks. Routing decisions that prolong the battery lifetime expectancy of the nodes will reduce nodes' failure probability.

However, the original CPN algorithm relies on semi-static networks whose neighboring information is known prior to the routing process. Although the algorithm is able to handle reasonably well individual link disconnections, it is unable to deal with frequent disconnections and reconnections at different locations.

In ad hoc networks, neighboring information needs to be learned dynamically. One way to achieve this goal is to make nodes periodically send out a signal (*beacon packet*) by means of local broadcasts. Local broadcasts (or *neighborcasts*) do not necessarily reach all nodes on the network. Instead, they are only received by immediate neighbors of the transmitting node, which would learn the existence of the node as a current neighbor. However, this approach leads to an unnecessary consumption of resources even when there is no traffic demand [1, chap 9].

To maintain low resource consumption, most ad hoc routing proposals use a broadcast query and await-reply cycle that is triggered on demand. This procedure allows nodes to discover routes and neighbors at the same time. As described in the previous section, this broadcast cycle floods the network (either totally or partially) in the forward direction (from source to destination).

Our ad hoc routing solution [2] employs an on-demand approach. In this algorithm, smart packets make routing decisions, as in CPN, but in addition, they may create partial broadcast query and await-reply cycles that assist in the discovery of neighbors and routes, as needed.

2 ROUTING IN MOBILE AD HOC NETWORKS

Previous proposals for routing in ad hoc mobile networks can be classified as table driven protocols (proactive) and as source-initiated on-demand driven protocols (reactive) [3]. While proactive protocols require global information about the network to maintain routing information for every possible source-destination pair, reactive protocols initiate a route discovery only when it is needed

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by a node. Proactive protocols are in general more expensive in terms of use of network resources than reactive protocols, since they require a periodic transmission of routing tables by the nodes. Destination-Sequenced Distance-Vector routing (DSDV) [4], Wireless Routing Protocol (WRP) [5], Clusterhead Gateway Switch Routing (CGSR) [6] are examples of proactive protocols where the control packet overhead grows as $O(n^2)$ where n is the number of nodes. Global State Routing (GSR) [7] takes the idea of link state routing to reduce routing messages by sending them only when changes occur in the status of links. Fisheye State Routing (FSR) [8] is an attempt to reduce the still high routing overhead of GSR by using different update frequencies depending on the distance to other nodes.

Most on-demand protocols use a variation of flooding, sending a route request packet to find a route from a source to a destination. Flooding can be restricted by requiring that each node process each request packet at most once, limiting the control packet overhead to $O(n)$. In order to accelerate route discovery, many on-demand routing proposals stop the route search process when the request packet encounters a node with knowledge of a route to the destination: DSR [9], AODV [10, 11], LMR [12]. However, this condition does not reduce the overall complexity because it only prevents the continuation of that particular replica of the route request. A way to reduce route discovery complexity is offered by Location Aided Routing (LAR) [13] and geoTORA [14], where the propagation area of the flooding is restricted by using location information of the nodes based on Global Positioning System (GPS) information at each node.

Although route discovery in reactive protocols is triggered only when needed, some proposals for source-initiated on-demand driven protocols do require a relatively "expensive" periodic transmission of a control packet [1] to maintain updated information about neighbors and their link status. ABR [15] and SSR [16] use periodic beacons to determine the link stability of a node in order to use this information in the routing process. The Temporally Ordered Routing Algorithm (TORA) [17, 18, 19] runs over the Internet MANET Encapsulation Protocol (IMEP) [20] which in turn also uses the beacon approach.

Because the advances in battery technologies are behind the pace of computing and storage technologies [21], there exists an increasing interest in developing power-aware systems for wireless, mobile applications.

Research in power-efficient techniques embraces all seven layers of the OSI model. Power conserving methods have been investigated in the design of hardware [22], operating systems, and applications, ranging from the design of energy-efficient schedulers for processors [23, 24] to power-aware applications for database transactions [25]. In the context of power efficient, routing proposals, Singh, et al, [26] investigated the use of power-aware metrics in the calculation of the shortest paths. The metrics described the power required for transmitting and receiving a packet on a link, so as to minimize the end-to-end power requirements for routing with a Dijkstra or Bellman-Ford algorithm. However, the proposal did not take into account the remaining energy in the nodes, which may produce a severe drain of energy in the batteries of the nodes on the least-cost route. Other proposals overcome this problem by using of battery lifetime information. Toh [27] proposed a new metric, which calculated the summation of the inverses of the remaining battery capacities of the nodes on the path. Furthermore, the author proposed the *Min-Max* algorithm to maintain a fair use of resources by avoiding the use of nodes with the least battery capacity on the network. In [28], the authors propose an algorithm (denoted by *max-min* zP_{min}) that computes the paths with the minimal energy consumption while maximizing the minimal residual power of the network.

The *power-aware source routing* (PSR) [29] protocol uses a modified version of DSR that includes power computation. Like DSR, PSR sends out route requests to find new routes. All nodes but the destination calculate a link cost, which consist of the remaining battery capacity and the transmission power of the node, and include this information in the header of the request packets. The destination waits a time interval after the arrival of the first route request, so as to receive more than one possible route, and then selects the one with the minimum cost.

The *adaptive fidelity algorithm* [30] operates on top of on-demand ad hoc routing protocols, such as AODV and DSR, and saves battery power by turning off certain radios whenever the applications allows a reduction in the quality of the connections. The algorithm trades quality for battery lifetime, network bandwidth, or a number of active sensors.

Finally, localization information has been used for routing [31, 32] to restrict the area of searching and consequently to reduce the overall power consumption of the network. However, the use of GPS devices, to obtain the localization information, increases the energy consumption of the nodes.

3 AD HOC CPN

Similarly to CPN, *Ad-Hoc Cognitive Packet Networks* (AHCPN) use three types of packets to achieve learning of routes and transport of data packets: *smart packets* (SP) are responsible for the discovery and maintenance of routes, *dumb packets* (DP) transport payload, and *acknowledgment packets* (AP) distribute routing information and provide confirmation of delivery to the source.

All these three types of packets have a similar structure (Figure 1). They contain a header, a *cognitive map* (CM) (to store routing information), and a data area. The header contains routing control information, for example, a destination address, packet length, etc. In the cognitive map, packets record routing metrics as they move on a network. The data area is used only by dumb packets for payload. Smart packets explore the network attempting to achieve their routing goals. As they travel, they record their path in their CM. Also, they collect additional characteristics about the path, for example the arrival time (timestamp) at each hop, which is used by future smart packets to make better routing decisions.

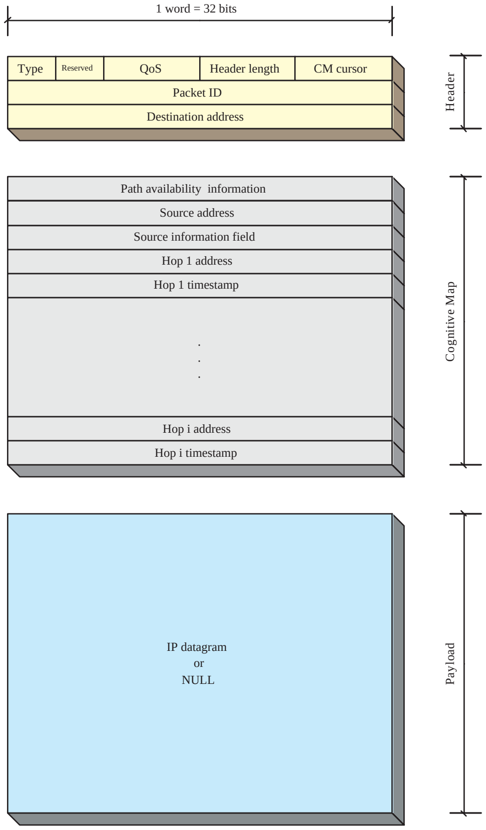


Figure 1: Packet format in AHCPN.

1. *Type* (4 bits)—identifies the packet type (Table 1).

Table 1: AHCPN packet type field.

type	use
0	dumb packet
1	smart packet
2	acknowledgment originated by a dumb packet
3	acknowledgment originated by a smart packet
4-15	reserved for future use

2. *QoS* (4 bits)—indicates the desired quality of service for the packet. The quality-of-service goal determines the reinforcement learning function to be used to update the random neural network in the CPN algorithm. The QoS field is set at the source node both from information retrieved from the original IP packet and from pre-defined administrative information. Table 2 describes the various values defined.

Table 2: QoS field in AHCPN packet.

bit	use
0	delay
1	jitter
2	general packet loss
3	link quality
4	energy
5-8	reserved for future use

3. *Header length* (8 bits)—indicates the length of the packet header plus the length of the cognitive map in words of 32 bits.
4. *Cognitive map index*—indicates the position in the cognitive map of the node transmitting the packet.
5. *Packet identification* (32 bits)—uniquely distinguish the packet. Acknowledgments carry the same packet identification as their originators (dumb or smart packets). The identification is used at the source node to remove packets waiting for retransmission, after the corresponding acknowledgment arrives. In addition, smart packets leave a copy of their packet identification in the nodes to identify previously visited nodes.
6. *Destination address* (32 bits)—uses an IPv4 addressing space.
7. *Cognitive map* (variable)—is an area where packets store information about the network. A cognitive map in AHCPN consists of the following field:
    - *Source and intermediate hop addresses*—uses IPv4 address format. Smart packets attach a new record with every node that they visit. On the other hand, dumb and acknowledgment packets carry the cognitive map given to them at the source node.
    - *Timestamp fields*—record the arrival time at each intermediate node. In the case of the source node, the record indicate the packets' departure time.
    - *Path availability information field*—expresses the probability to find all nodes and links available for routing from the present location to the destination (calculated from battery lifetime of the nodes and link quality of the channels). Requires either 32 or 64 bits.

8. *Payload*—the area where dumb packets transport IP datagrams.

To make a routing decision in a node, a smart packet constructs a random neural network containing as many neurons as possible next-hop decisions, and adjusts the weights of the RNN with a reinforcement learning based algorithm from the information in the mailbox. The most excited neuron of the neural network in steady state determines the next-hop decision. At the destination, the cognitive maps of the packets are processed to remove possible loops before sending them to the source into acknowledgment packets. To overcome problems associated with topological changes, a small number of smart packet decisions are replaced by local broadcasts (controlled by a pre-selected broadcast-to-unicast ratio). Broadcasts are also used as a last-resource alternative whenever sufficient information is not available to make a regular RNN/RL decision.

Acknowledgments follow the reverse path that is recorded in their cognitive map. They update the mailboxes on their path with the information stored in the packet. For example, the timestamp stored in the cognitive map and the current arrival time are used to calculate the round-trip delay to the destination. Acknowledgments also store the route discovered by the corresponding smart packet in a route cache at the source node. Dumb packets use the routes in the route cache to transport payload (source routing). As in smart packets, dumb packets also collect routing metrics as they move, which are used later to maintain the information in the mailboxes.

Nodes are used as storage areas and processing units. A mailbox is a storage area where packets read or write information. Acknowledgement packets deposit in a mailbox the routing metrics acquired by a previous SP or DP. Smart packets use the information stored in a mailbox to update the weights of the RNN to make a routing decision. Nodes also store and execute the code for the RNN.

4 POWER-AWARE ROUTING GOAL

Smart packets employ a routing goal to update RNN weight matrices [33]. To enable power awareness, we introduce path availability to quantify the battery lifetime involved on a path. We define *path availability* as the probability to find all nodes and links available for routing on a path. Formally, suppose that a smart packet takes the path: $(n_1, n_2, \ldots, n_d)$, where n_i represents the i-th node on the path and (n_i, n_{i+1}) represents the link between nodes n_i and n_{i+1}.

Assume that the node n_i is available for routing with probability $P_n(n_i)$ and that the link (n_i, n_{i+1}) is available with probability $P_l(n_i, n_{i+1})$. We define the path availability $P_p(n_i, n_d)$ as:

$$P_p(n_i, n_d) = \prod_{j=i}^{d-1} P_n(n_{i+1}) P_l(n_i, n_{i+1}) \qquad (1)$$

We formulate a recursive, combined routing goal function G_i as follows which consist of round-trip delay and path availability:

$$G_i = P_p(n_i, n_d) D(n_i, n_d) + [1 - P_p(n_i, n_d)](T_o + G_i) \quad (2)$$

where $D(n_i, n_d)$ is the round-trip delay from n_i to n_d and T_o is a predefined timeout interval.

In real systems, many factors contribute to the values of P_n and P_l. For the purposes of this paper, we assume that $P_l = 1$. Because batteries are the major source of energy in mobile nodes, they represent one major factor in determining P_n. To provide greater portability, batteries need to be small and lightweight, which unfortunately restricts the total energy that they can carry. Once the batteries exhaust their energy, they need to be replaced or recharged, which typically reduces the independence of the mobile node to a few hours of operation.

The energy consumption, in communication related tasks, depends on the communication mode of the node. A node may be transmitting, receiving, or in idle mode. Transmission naturally consumes more energy than the other two modes. From the routing perspective, our interest is in selecting routes in such a way that the transmission and reception of packets is distributed on the network so as to maximize the overall average battery lifetime of the nodes. Therefore, we are interested in getting smart packets to select—with greater frequently—the nodes with the longest remaining battery lifetime.

Let us set $P_l(n_i, n_{i+1}) = 1$ in Equation 1, for all $i \in [1, d-1]$, to simplify our discussion. Therefore:

$$P_p(n_i, n_d) = \prod_{j=i}^{d-1} P_n(n_{i+1}) \qquad (3)$$

Assume B_i is the remaining battery lifetime of node n_i. We formulate $P_n(n_i)$ in terms of B_i as:

$$P_n(n_i) = \frac{B_i}{B_m} \qquad (4)$$

where B_m is the lifetime of a fully charged battery. From Equation 3 and Equation 4 we obtain the desired path availability to destination n_d from any node on the path:

$$P_p(n_i, n_d) = \prod_{j=i}^{d-1} \frac{B_{j+1}}{B_m}$$

5 SIMULATION

The experiments were performed on the topology depicted in Figure 2 with the purpose of observing the adaptation of routing with or without energy information. The network consisted of stationary, wireless nodes, whose location created the desired network topology. The dotted lines that converge on the nodes represent a unique transmission medium (a single interface). All the nodes started with a full charged battery except nodes 1 and 3, which started with only 25% of their full charge. The battery-consumption model explained previously was intentionally disabled during this experiment to force nodes to always report the same values.

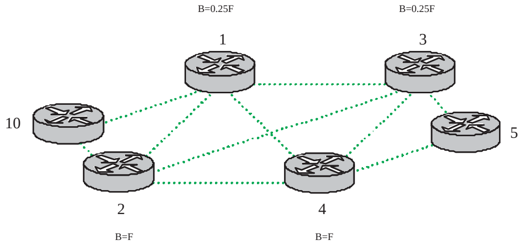


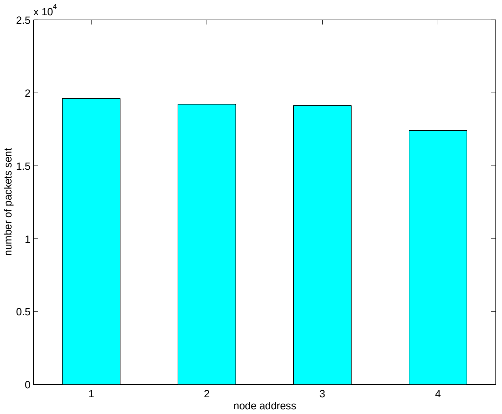
Figure 2: Wireless topology.

The procedure consisted of sending a single packet stream at a constant bit rate (CBR) of 100 packets per second (packets of 1000 bytes) from node 0 to node 5, and then measuring the number of times that each core node (nodes 1–4) was used for routing (i.e. the number of transmissions of each core node).

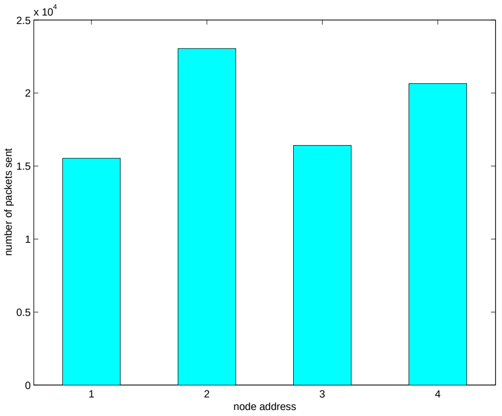
The battery-consumption model assumes that the battery lifetime of a node reduces linearly with time whenever the node is not transmitting or receiving [34, 35, 36, 37] any packet. Energy consumption at the receiver and transmitter circuitry is simulated by reducing the battery level $k\epsilon_r$ and $k\epsilon_t$ units, respectively, for each packet of k bits. The values of ϵ_r and ϵ_t model the characteristics of particular wireless network adapters that normally provide $\epsilon_t >> \epsilon_r$. In the simulations that we report in this paper, we have employed an exaggerated high value of ϵ_t to obtain observable results in a short time.

Figure 3(a) and Figure 3(b) report the node usage when smart packets attempted to minimize either round-trip delay or a combined function of round-trip delay and energy, respectively. When round-trip delay was the sole routing goal, the traffic load was well balanced among all routing nodes. On the other hand, there was a preference for using nodes 2 and 4 (as they had the longest battery lifetime of the four core nodes) when energy information was considered by the smart packets.

The corresponding battery levels of the four core nodes during the experiment are depicted in Figure 4(a) and Figure 4(b). When energy was included in the routing goal of the smart packets, nodes 1 and 3 were able to operate longer as they were less preferred in the route selection process. In addition, to extend the lifetime of low charged nodes, smart packets refuse to use nodes with battery levels below a predefined threshold (such nodes become passive for any connection). Nodes 1 and 3 became passive nodes after approximately 250 seconds of the start of the experiment and their battery consumption thereafter was the sole result of their normal operation.



(a) $G = f(D)$

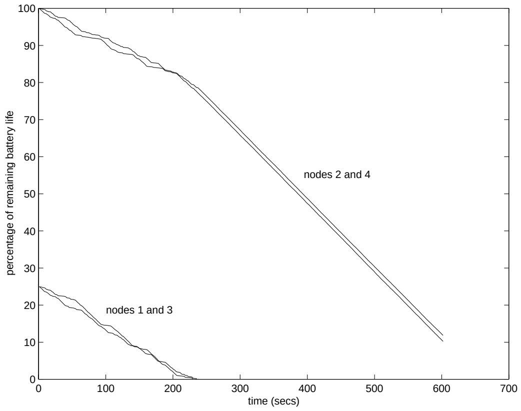


(b) $G = f(D, E)$

Figure 3: Number of packet departures per core node.

6 CONCLUSIONS

Both mobility and scarcity of resources are natural characteristics of wireless ad hoc networks which impede the use of the original cognitive packet networks algorithm as it requires a semi-static network topology to operate. We have discussed an extension to the CPN algorithm to enable their operation over these type of networks. Our approach was to introduce the use of broadcasts as a last-resource alternative for smart packets to move on the network. Furthermore, we enabled power awareness in the routing goal of smart packets to overcome the problems associated with power limitations in the



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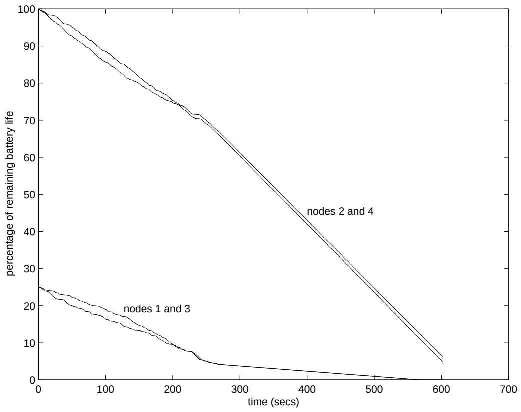

(b) $G = f(D, E)$

Figure 4: Percentage of remaining battery lifetime versus simulated time.

nodes. For this, we defined *path availability* as a new routing metric, which is able to model the quality and quantity of various network resources and we employed this metric to specifically quantify the battery lifetime of the nodes.

Our simulation model demonstrated how smart packets are able to take advantage of this new metric to establish paths with better energy, which extend the operative lifetime of the network. We are exploring additional use for cognitive packet based networks and the use of path availability to model additional network resources, that would help in the establishment of better quality paths for packets.

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