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Energy Conservation Techniques in Ad hoc Networks

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Abstract - **Energy is a limiting factor in the successful deployment of ad hoc networks since nodes are expected to have little potential for recharging their batteries. In this paper, we investigate the energy costs of wireless communication and discuss the mechanisms used to reduce these costs for communication in ad hoc networks. We then focus on specific MAC layer protocols can save energy by suspending the communication device during short-term idle periods in communication that aim to reduce energy consumption during both active communication and idle periods in communication.**

Keywords: **Communication-time energy, idle-time energy, energy-aware routing.**

I. INTRODUCTION

The limited energy capacity of mobile computing devices has brought energy conservation to the forefront of concerns for enabling mobile communications. This is a particular concern for mobile ad hoc networks where devices are expected to be deployed for long periods of time with limited potential for recharging batteries. Such expectations demand the conservation of energy in all components of the mobile device to support improvements in device lifetime [1] [2] [3]. In wireless networks, there is a direct tradeoff between the amount of data an application sends and the amount of energy consumed by sending that data.

Application-level techniques can be used to reduce the amount of data to send, and so the amount of energy consumed. However, once the application decides to send some data, it is up to the network to try to deliver it in an energy-efficient manner. To support energy-efficient communication in ad hoc networks, it is necessary to consider energy consumption at multiple layers in the network protocol stack. At the network layer, intelligent routing protocols can minimize overhead and ensure the use of minimum energy routes [4] [5]. At the medium access control (MAC) layer, techniques can be used to reduce the energy consumed during data transmission and reception [6] [7]. Additionally, an intelligent MAC protocol can turn off the wireless communication device when the node is idle [8] [9]. Communication in ad hoc networks necessarily drains the batteries of the participating nodes, and eventually results in the failure of nodes due to lack of energy. Since the goal of an ad hoc network is to support some desired communication, energy conservation techniques must consider the impact of specific node failures on effective communication in the network. At a high level, achieving the desired communication can be associated with a definition of network lifetime. Current definitions of network lifetime include:

1) the time when the first node failure occurs 2) the fraction of nodes with non-zero energy as a function of time [10] [11] [12], 3) the time it takes the aggregate delivery rate to drop below a threshold [13], or 4) the time to a partition in the network. In the context of any of these definitions, it may also be useful to consider node priority in the definition of lifetime. For example, the network lifetime could be defined as the time the first high priority node fails. In general, one static definition of lifetime does not fit all networks. In this paper, we present approaches to energy conservation that minimize energy consumption for communication in ad hoc networks. However, these approaches can be tuned to support the desired communication and the definition of network lifetime as needed by the specific ad hoc network.

Energy conservation can be achieved in one of two ways:
- Saving energy during active communication &
- Saving energy during idle times in the communication.

The first targets the techniques used to support communication in an ad hoc network and is typically achieved through the use of energy-efficient MAC and routing protocols. The second focuses on reducing the energy consumed when the node is idle and not participating in communication by placing the node in a low-power state. In this paper, we first define the costs associated with communication in ad hoc networks and then discuss the use of communication-time and idle-time energy conservation.

II. ENERGY CONSUMPTION IN AD HOC NETWORKS

In general there are three components to energy consumption in ad hoc networks. First, energy is consumed during the transmission of individual packets. Second, energy is consumed while forwarding those packets through the network. And finally, energy is consumed by nodes that are idle and not transmitting or forwarding packets. To understand how and when energy is consumed in ad hoc networks, it is necessary to consider these costs for data packets forwarded through the network and for control packets used to maintain the network. To lay the groundwork for discussing energy efficient communication protocols in ad hoc networks, we define these costs for communication and introduce energy-saving mechanisms used by many protocols.

2.1 Point-to-Point Communication

The basis for all communication in ad hoc networks is the point-to-point communication between two nodes. At each node, communication impacts energy consumption in two ways. First, the wireless communication device consumes some base energy when it is activated and idle (see Table 1. Note that specifications for most current wireless devices do not provide a differentiation between idle and receive costs). Second, the act of transmitting a packet from one node to another consumes energy at both nodes. The transmit power level at the sender (see Table 1). Reception energy depends on the base reception costs in the wireless card. The amount of time needed for the packet transfer determines the amount of time the card must be active, and so directly determines the energy consumed by the base card costs for both transmission and reception. This time is determined by two factors: the control overhead from packet transmission and the rate at which the packet is transmitted.

The per-packet control overhead is determined by the mechanisms of the medium access control (MAC) protocol. Depending on the chosen protocol, some energy may be consumed due to channel access or contention resolution. For example, in IEEE 802.11 [8], the sender transmits an RTS (ready to send) message to inform the receiver of the sender's intentions. The receiver replies with a CTS (clear to send) message to inform the sender that the channel is available at the receiver. The energy consumed for contention resolution includes the transmission and reception of the two messages. Additionally, the nodes may spend some time waiting until the RTS can be sent and so consume energy listening to the channel. In this chapter, we focus on the use of RTS/CTS-based protocols. While it has been shown that such protocols may not be optimal for throughput [14], there is no widely accepted alternative for communication in mobile ad hoc networks.

Card	Transmit Power Levels
Cisco Aironet 350	100,50,30,20,5 mW
Socket Low Power SDIO	Max 25 mW

Table 1. Transmit power levels for selected wireless cards with power control capabilities.

Card	Rates
IEEE 802.11 b.g	11,5.5,2,1 Mbps
IEEE 802.11 a.g	54,48,36,24,18,12,9,6 Mbps
Mica2 Motes	12 Mbps

Table 2. Transmit rates for selected wireless card types.

Once channel access and contention resolution have determined that a packet may be sent, many wireless network cards provide multiple rates at which the data can be transmitted, which determines the time needed to send the data (See Table 2). The specific transmission rate used is determined by a number of factors, including the signal-to-noise ratio (SNR) and the target reliability of the transmission [5] [15] . In general, the signal strength at the receiver, which determines the SNR, varies directly with the sender's transmit power level and varies inversely with the distance between the sender and the receiver. This relationship can be formulated as:

$$ReceiveSignal \times TransmitPower/Distance^{n}$$

where the path loss exponent n varies from 2 to 6 [16], although is most commonly used as 2 or 4. For the receiver to correctly receive the packet, the SNR must be over a certain threshold. As long as the receive SNR is maintained above this threshold, the transmit power level at the sender can be reduced, directly reducing energy consumption at the sender. The adaptation of the sender's transmit power level is called *power control* and is the main tool used to conserve energy during active communication. For the remainder of this chapter, we use power level to mean transmit power level. Finally, energy is consumed to compensate for lost packets, generally via some number of retransmissions of the lost packets. While reliability is generally the domain of the transport layer, the MAC layer in most wireless devices compensates for some packet failure by retransmitting the packet up to some retransmit limit number of times before considering the packet lost. For current energy conserving protocols, this cost is only considered by protocols that aim to avoid low quality channels and so avoid needing to retransmit packets.

2.2 End-to-End Communication

End-to-end communication in ad hoc networks is supported by all nodes participating in route maintenance and data forwarding. Therefore, network wide energy consumption includes any control overhead from routing protocols, including route setup, maintenance and recovery, as well as the impact of the chosen routes on the energy consumed at the intermediate nodes to forward data to the receiver. The choice of a specific route is determined by the metrics used in the routing protocol. Initial protocols use hop count as a primary metric [17] [18], although delay often implicitly impacts route choices [19]. More recent protocols suggest the use of extended metrics such as signal strength [20], stability [21] and load [22], all of which impact performance and so implicitly impact energy consumption [23]. Energy can also be used explicitly to choose routes that minimize energy consumption [24] or avoid nodes with limited energy resources [25]. Additionally, when a route breaks, it is essential to use energy-efficient mechanisms to find a new route, avoiding a reflooding of the network whenever possible. At the network layer, *energy-efficient routing protocols* combine these techniques with power control for additional energy conservation during active communication.

III. ENERGY CONSERVATION APPROACHES

Once all of these costs are understood, two mechanisms affect energy consumption:

Communication Time Energy Conservation and Energy Aware Routing. If these mechanisms are not used wisely, the overall effect could be an increase in energy consumption or reduced communication in the network.

3.1 Communication-Time Energy Conservation

The goal of communication-time energy conservation is to reduce the amount of energy used by individual nodes as well as by the aggregation of all nodes to transmit data through the ad hoc network. Two components determine the cost of communication in the network. First, direct node-to-node transmissions consume energy based on the power level of the node, the amount of data sent and the rate at which it is sent. The amount of data is determined by the application and the rate is determined by the characteristics of the communication channel.

Although the transmission rate can also be adapted by the sender [26], we do not consider such rate control in this chapter. However, the power level can be controlled by the node to reduce energy consumption. Such *power control* must be performed in a careful manner since it can directly affect the quality and quantity of communication in the network. Second, energy is consumed at every node that forwards data through the network. Such costs can be minimized using *energy-aware routing* protocols. This section first discusses the use of power control and its impact on communication in ad hoc networks. We then present power control protocols and energy-aware routing protocols that aim to minimize energy consumption for communication in the network.

3.2 Energy-Aware Routing

Routing protocols for ad hoc networks generally use hop count as the routing metric, which does not necessarily minimize the energy to route a packet [27]. Energy-aware routing addresses this problem by finding energy-efficient routes for communication. At the network layer, routing algorithms should select routes that minimize the total power needed to forward packets through the network, so-called *minimum energy routing.* However, minimum energy routing may not be optimal from the point of view of network lifetime and long-term connectivity, leading to energy depletion of nodes along frequently used routes and causing network partitions. Therefore, routing algorithms should evenly distribute forwarding duties among nodes to prevent any one node from being overused (i.e., *capacity-aware routing*). Hybrid protocols explore the combination of minimum energy routing and capacity-aware routing to achieve energy efficient communication while maintaining network lifetime.

IV. MINIMUM ENERGY ROUTING

The routing metric used by minimum energy routing is the per-hop minimum power level P (i, j) needed for node i to reach node j The total power level for route r, P_r, is the sum of all power levels P (i, j) along the route:

$$P_r = \sum^{D-1} P(ni, ni+1),$$

where nodes n_O and n_D are the source and destination, respectively.

Minimum total transmission power routing (MTPR) [24] [28] finds a minimal power route such that:

$$P_s = \min_{r \in A} P_r,$$

where A is the set of all possible routes. Based on a given minimum energy topology that defines the maximum power level for all nodes, MTPR finds the minimum energy routes optimizing the power level for each hop. In contrast, PARO [5] is a minimum energy routing protocol ad hoc networks that discovers minimum energy routes on demand. PARO assumes that all nodes are located within direct transmission range of each other and that a source node initially uses the threshold power level to reach the destination. Each node capable of receiving the packet determines if it should intervene and forward the packet to the destination itself to reduce the energy needed to transmit the packet.

Although, PARO is designed for one-hop ad hoc networks, the optimization can be used by any pair of communicating nodes, which allows extending PARO to multi-hop networks. Given this definition of minimal power routing, both MTPR and PARO favor routes with more hops (i.e., more shorter hops vs. fewer longer hops). Since the power level, and so the transmission energy consumption, depends on distance (proportional to d^n), the energy consumed using many short hops may be less than the energy consumed using fewer longer hops [5] [15].However, the more nodes involved in routing, the greater the end-to-end delay. Additionally, a route consisting of more hops is likely to be unstable due to the higher probability of the movement or failure of intermediate nodes. Furthermore, both protocols ignore the energy consumed at the relay nodes to receive the packets. Based on these observations, the routes found by MTPR and PARO may not be efficient. To overcome these problems, the energy consumed when receiving the packet should be included into the routing metric [29] [30], which is likely to result in the use of shorter routes. An even more accurate metric should include the total energy consumed in reliably delivering the message to its destination (e.g., the energy cost of link-layer retransmissions). In particular, it is essential to avoid links with relatively high error rates to reduce the energy consumed to reliably transmit packets.

4.1 Capacity-Aware Routing

Assuming all nodes in the network are equally important, no node should be used for routing more often than other nodes. However, if many minimum energy routes all go though a specific node, the battery of this node is drained quickly and eventually the node dies. Therefore, the remaining battery capacity of a node should be used to define a routing metric that captures the expected lifetime of a node, and so, the lifetime of the network.

Given c^t_i, the battery capacity of node i at t the function $f_i(c^t_i)$ captures the cost to forward packets for a node i This cost can be defined as the inverse of the remaining battery capacity and modeled as [25] [31]:

$$f_i(c^t_i) = \frac{1}{C_i^t},$$

The battery cost metric for route r at time t, R_r, can then be determined as:

$$R_r = \max_{i \in r} f_i(c_i^t),$$

Therefore, the desired capacity-aware route s, where A is the set of all possible routes satisfies:

$$R_s = \min \{ R_r | r \in A \},$$

It must be noted that the choice of

$$f_i(c^t_i) = \frac{1}{C_i^t},$$

does not consider the effect of the traffic load on the node battery capacity. To this end, *drain rate* is proposed as a metric to measure the *energy dissipation rate* at a given node

[32]. The *Minimum Drain Rate (MDR)* algorithm determines the battery cost metric of route r, R_r, as:

$$R_r = \min_{i \in r} \frac{c_i^t}{DrainRate_i} ,$$

and capacity-aware route satisfies:

$$R_s = \max \{ R_r \mid r \in A \} ,$$

Incorporating the battery cost into the routing protocol prevents a node from being overused. However, there is no guarantee that minimum energy routes are found by the routing protocol. Therefore, capacity-aware routing may consume more energy to route traffic, which can reduce the lifetime of the network.

V. HYBRID SOLUTIONS (MINIMUM ENERGY/MAXIMUM CAPACITY)

Hybrid solutions try to find minimum energy routes while maximizing the lifetime of the network. To this end, *Conditional Max-Min Battery Capacity Routing (CMMBCR)* [29] follows minimum energy routing as long as some routes between the source and the destination have sufficient remaining battery capacity (i.e., above a certain threshold). The battery capacity of a route r, R^c_r, is:

$$R_r^c = \min_{i \in r} c_i^t ,$$

and minimum energy routing is followed as long as:

$$R^c_r \geq \delta \text{ for any } r \in A ,$$

If all routes are below the energy threshold capacity-aware routing is used to determine the route to choose. The benefit of such an approach comes from the fact that capacity-aware routing is only used when critical nodes in the network have low battery levels. The efficiency of the CMMBCR depends on the energy threshold δ However, it is not straightforward how to determine The *Conditional Minimum Drain Rate (CMDR)* protocol [32] limits route choices for MTPR to routes only containing nodes with a lifetime higher than a given threshold

(i.e., $\frac{c_i^t}{DrainRate_i} \geq \gamma$,)

If no such route exists, CMDR switches to the MDR scheme. To overcome the difficulty of selecting a value for δ in CMMBCR, CMDR uses γ which is an absolute time value based on the current traffic conditions.

The *max-min* $Z \,.\, P_{min}$ algorithm [15] minimizes energy consumption $P_{min,}$ and maximizes the minimum residual energy of the nodes. If the minimum energy route has energy consumption routes with higher minimum residual energy can be used as long as the energy consumption is less than $Z \,.\, P_{min}$ the Z-factor, similar to CMDR, is computed based on the minimum lifetime of the nodes.

All three of the above algorithms find minimum energy routes when nodes have sufficient residual energy and switch to capacity-aware routing as the battery capacity of the nodes decreases or the lifetime decreases beyond a predefined threshold. In contrast, the cost metric of a link (i,j) can be chosen to represent both the transmission power cost of the link and the initial and residual energy of node i [4] [31]. Specifically, link cost, can be computed as [4]:

$$Cost_{i,j} = e\alpha(c^t_i)^{-\beta}(c^o_i)^{\theta} , \quad Equation\ .1$$

where is the energy used to transmit and receive on the link, c^t_i, is the current capacity of node i,c^o_i is the initial capacity of node i and and γ, β *and* θ are non-negative weights. The link cost function computed in this fashion emphasizes the energy expenditure term when nodes have high battery capacity. As the residual energy of the nodes decreases, the battery capacity term is more emphasized.

To avoid depletion of nodes along common minimum energy routes, another approach is to occasionally use sub-optimal routes [33]. Basically, possible routes between a source and destination are used with a probability based on the energy metric in Equation .1

VI. IDLE-TIME ENERGY CONSERVATION

Effective idle-time energy conservation necessarily spans all layers of the communication protocol stack. Each layer has access to different types of information about the communication in the network, and thus, uses different mechanisms to support energy conservation. MAC layer protocols can save energy by suspending the communication device during short-term idle periods in communication (i.e., operate in a power-save mode). Such fine-grained control requires integrated knowledge of transitions between device suspend and resume in the MAC protocol to insure the communicating nodes are both awake. The delay overhead from waking up a suspended device can negatively impact communication in the network and so power-save modes should not always be used. Power management protocols integrate global information based on topology or traffic characteristics to determine transitions between active mode (i.e., never suspend) and power-save mode.

VII. CONCLUSION

Energy conservation in ad hoc networks is a relatively new field of research. In this paper, we have presented some of the recent proposals and specifications for achieving that goal. It is clear that there is still room for new approaches that tackle this extremely complex problem of balancing energy conservation with communication quality in dynamic ad hoc networks.

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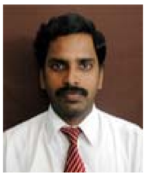

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