

Energy Efficient AODV Routing in CDMA Ad Hoc Networks Using Beamforming

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Abstract—In this paper, we propose an energy aware on-demand routing protocol for CDMA mobile ad hoc networks, for which improvements in the energy consumption are realized by both introducing an energy based routing measure and by enhancing the physical layer performance using beamforming. Exploiting the cross-layer interactions between the network and the physical layer leads to a significant improvement in the energy efficiency compared with the traditional AODV protocol and ensures a faster response to system changes, and reduced overhead.

I. INTRODUCTION

In ad hoc networks, every node must participate not only as a host, but also as a router forwarding packets to their destinations. When network topology changes unpredictably due to node movements, the hosts need to determine the routes to other nodes frequently. Ad-hoc On-Demand Distance Vector routing protocol (AODV) proposed in [1] is one of the developed protocols that enable routing with continuously changing topologies. AODV establishes routes when they are first needed and does not maintain routes to destinations that are not in active communication. There have been several studies on the performance of AODV protocol and other on demand ad-hoc routing protocols ([2], [3]). However, these earlier studies did not focus explicitly on the energy efficiency of the protocols.

With the tight energy constraints in the ad hoc network, the energy consumed for data transmission, routes establishment and maintenance should be kept as low as possible. The energy consumed for the correct transmission of a packet is an important QoS measure for the ad hoc networks [5]. There has been significant effort in proposing energy efficient routing protocols (e.g. [6],[8]), with a more recent focus on cross-layer design solutions (e.g. [5], [13]). However, previously proposed solutions do not consider on-demand routing for mobile ad hoc networks.

In recent years, beamforming technology has been recognized as a breakthrough with its potential to unshackle the capacity limitations of ad hoc networks. The benefits provided by beamforming, such as longer transmission range and reduced interference have been studied in [9]. Moreover, a vast research literature focuses on analyzing the performance of medium access control (MAC) protocols using beamforming (e.g. [10] [11]). However, the performance advantages and the tradeoffs

associated with the interactions between beamforming and routing, are less understood.

In this paper, we propose an energy aware AODV (EA-AODV) protocol. The improvements in the energy consumption are obtained by both introducing an energy based routing measure and by enhancing the physical layer performance using directional antennas. Moreover, compared with the traditional AODV protocol, exploiting the cross-layer interactions between the network and the physical layer leads to a significant improvement in bandwidth and energy efficiency, and ensures a faster response to system changes with reduced overhead transmissions.

Our simulation results for a CDMA ad hoc network show that an optimal signal-to-interference (SIR) target can be determined by combining the requirements for the considered performance metrics, such as energy, end-to-end latency and overhead energy for maintenance of the routing table.

II. SYSTEM MODEL

We consider an ad hoc network consisting of N mobile nodes. For simulation purposes, the nodes are assumed to have a uniform distribution over a square area, of dimension $D^* \times D^*$. It is assumed that each node generates traffic to be transmitted towards a randomly chosen destination node. The traffic can be relayed through intermediate nodes. Consequently, a node can also act as a router forwarding packets to the destinations. To accomplish this, the node must determine the route of an outgoing packet according to a pre-set routing metric.

For the multi-access scheme, we employ synchronous direct-sequence CDMA. All nodes use independent, randomly generated and normalized spreading sequences of length G . The transmitted bits are detected using a matched filter receiver. A link is considered to be available if the ratio of signal-to-interference (SIR) at the receiver is above a pre-defined threshold. By setting the SIR threshold properly, the mobile hosts are protected from draining their energy by transmitting over a poor link. On the other hand, the SIR threshold level can affect the network connectivity: for a high SIR threshold, fewer links will be available for transmission. For mobile users, frequent changes in topology are triggered by the nodes' mobility, and a higher SIR threshold will result in an increased effort to find new routes, and thus higher overhead.

III. ENERGY AWARE ROUTING METRIC

Ad Hoc on-demand Distance Vector routing (AODV) is used for ad hoc networks to create routes as they are needed. Given the same sequence number, traditional AODV protocol selects the route with a fewer number of hops to the destination, without specifically accounting for the links' quality.

To improve the energy efficiency for the AODV protocol, we consider as a routing metric the energy required for the correct transmission of a packet from mobile node i to node j , E^{ij} [4]:

$$E^{ij} = \frac{MP_j}{RP_c(\gamma_{ij})}, \quad (1)$$

where M denotes the length of the packet, P_j is the transmission power, R represents the data transmission rate and $P_c(\gamma_{ij})$ is the probability of correct reception of a packet, with γ_{ij} equal to the SIR of link (i,j) . The function in (1) depends on the details of the data transmission, such as modulation, coding, radio propagation and receiver structure. We choose the same data transmission model as the one in [4], which gives

$$P_c(\gamma_{ij}) = (1 - 2BER_{ij})^M, \quad (2)$$

where BER_{ij} is the bit error rate for link (i,j) . For non-coherent frequency shift keying (FSK),

$$BER_{ij} = 0.5 \exp\left(-\frac{\gamma_{ij}}{2}\right). \quad (3)$$

The energy requirement for correct transmission of a packet on a specific route (from a source node to its corresponding destination) can be determined to be [5]:

$$E_r = \sum_{link(i,j) \in r} E^{ij}, \quad (4)$$

where r is a route.

Obviously, selecting the paths with a minimum energy requirement improves the energy efficiency of the network. Based on this observation, the energy per packet on a route can be used as the routing criterion to improve the energy efficiency of the network.

IV. ENERGY AWARE AODV

In our proposed Energy Aware AODV (EA-AODV) protocol, the energy per packet on a route is employed as the routing metric. The basic routing mechanism is described in the following. When a node S needs a route to some destination D , it will broadcast a Route Request to its neighbors. The latest sequence number of its destination is broadcasted as well. Each intermediate node forwarding the Route Request records a reverse route back to node S (according to our proposed energy efficient metric). Then, node S can transmit data packet along this energy efficient path.

As the nodes move around randomly, the link quality between nodes may change unpredictably. The link quality depends on the achieved signal-to-interference ratio (SIR). When the SIR between node i and node j , say γ_{ij} drops

below the system SIR threshold γ_{Th} , link (i, j) is considered to be broken. When a link goes down, any node that has recently forwarded packets to a destination using this link is notified by an Unsolicited Route Reply message, and the route to the destination that contain this broken link is disabled. A new Route Discovery process as described above is initiated to find a new route to the destination.

In order to maintain routes, the routing protocol needs an effective way to detect the link breakages. AODV usually requires that each node periodically transmit a HELLO message with a default rate of once per second. However, HELLO messages create extra control overhead and increase bandwidth consumption. Furthermore, once a link breaks, changes in the links' quality due to mobility are not acknowledged at the network level until some pre-defined number of Hello messages have been lost. Thus, until an action occurs, the energy of the mobile host is wasted for transmitting over a route that actually has a broken link. In the AODV specification document [1], it is suggested that an alternative method may be used when physical layer or link layer information is employed to help the nodes detect link breakages.

In our proposed energy aware AODV, cross-layer interactions between the physical and the network layer are exploited to improve the network performance. The link state information detected by the physical layer helps the routing scheme maintain the local connectivity at the network layer and yields an improvement in bandwidth savings and overhead energy efficiency, by eliminating the HELLO message used in the traditional AODV protocol. In EA-AODV, once the links connecting to the active neighbors become unavailable, the physical layer can detect this based on the received SIR for that particular link. An indication message can inform the network layer immediately to trigger a routing table update. Since EA-AODV establishes routes on demand, only the case of an active link's SIR falling below the threshold will trigger an information message for the network layer.

Moreover, the next-hop information for a traffic flow obtained from the routing scheme at the network layer determines the activated direction of the switched beams at the physical layer, thus further reducing the implementation complexity.

V. DIRECTIONAL ANTENNAS IN EA-AODV

Using directional antennas has the effect of improving the communication range, as well as reducing the interference, by focusing the radiation only in the desired direction and adjusting to changing traffic conditions or signal environments. Generally, smart antenna systems use sophisticated adaptive beamforming to achieve a better interference rejection performance. However, simple switched beam systems have the advantage of reduced cost and reduced implementation complexity. Switched beam systems provide a significant range extension and a considerable interference rejection capability, when the desired user is at the center of the beam.

In this work, we propose a joint routing and beamforming algorithm, based on energy aware AODV protocol. Each mobile node is assumed to be equipped with a switched beam

system consisting of K directional beams. Each of the beams has a conical radiation pattern P_g , spanning an angle of $2\pi/K$ radians with equal space [12]. The beams are assumed not to be overlapping. Starting from the 3 o'clock position, the beams are numbered from 1 to K clockwise. It is also assumed that the orientation is maintained by the nodes even when they move around. We employ directional antennas at the transmitter and omnidirectional antennas at the receiver.

In directional mode, the radio transmitter uses only the antennas that are active. For data packets transmission, only the beam pointing to the direction of the next hop will be activated. For relaying nodes transmitting multiple flows using the same beam, the transmissions are time-multiplexed. The broadcast control packets are transmitted using all beams simultaneously.

In our study, we assume that the nodes in the network are able to determine the relative direction of a neighbor node. Then, when node i wants to transmit a packet to node j , node i determines the direction of node j , Θ_{ij} , relative to itself. Let Θ_n denote the direction of the n -th beam for node i , where n is the index number of the beams as mentioned above. The index number of the beam that should be selected is the n which gives $\min |\Theta_{ij} - \Theta_n|$, $n = 1 \dots K$.

Suppose node i has a data packet to transmit. The next hop along the path is determined according to the routing table. At the physical layer, node i determines the relative direction of that next-hop node and the index number of the desired beam. Then, as described above, the control logic unit of switched beam activates the beam pointing to that particular direction.

For different traffic flows relayed by node i the traffic can be time multiplexed, if the destination nodes are located on the direction of the same beam, or simultaneously transmitted, if the destination nodes are located such that different beams can simultaneously be activated for transmission.

For broadcasting messages, for example a Route Request, all the beams are activated and the Request message is broadcasted to all directions in order to find a route to the destination.

While it has been shown in [7], that wireless bandwidth savings can be achieved by limiting the spread of the route discovery queries to specific regions, for simplicity, we use all directions broadcasting in this work.

Using directional antennas, and considering a simple free space propagation model, with propagation exponent $n = 2$, the Signal-to-Interference Ratio over link (i, j) , γ_{ij} , can be determined to be:

$$\gamma_{ij} = G \frac{p_i G_{ij}(\Theta_{ij}) / d_{ij}^2}{\sum_{k=1, k \neq i}^N (p_k G_{kj}(\theta_{kj}) / d_{kj}^2)}, \quad (5)$$

where G is the spreading gain, N is the number of nodes in the network, p_i is the transmission power of node i , and d_{ij} is the distance between node i and node j . $G_{ij}(\Theta_{ij})$ represents the antenna gain from i to j , and depends on Θ_{ij} , the relative direction of j to i . For directional transmitters and omnidirectional receivers, if Θ_{ij} is within one of the current active

beams in the switched beam system, the antenna gain G_{ij} is set to be equal to the main lobe gain according to the radiation pattern P_g ; otherwise, the antenna gain G_{ij} is considered to be the side lobe gain. At the receiver, omnidirectional antennas are employed with a gain equal to 1.

VI. SIMULATION RESULTS

To simulate the performance of our proposed routing algorithm, we have built a simulation environment based on an AODV simulator [14] developed for OMNET++ [15]. We have simulated four different scenarios:

- Traditional AODV with minimum hop routing for CDMA ad hoc mobile networks using omnidirectional antennas;
- Proposed AODV with energy as routing metric for CDMA ad hoc mobile networks using omnidirectional antennas;
- Traditional AODV with minimum hop routing for CDMA ad hoc mobile networks using directional antennas;
- Proposed AODV with energy as routing metric for CDMA ad hoc mobile networks using directional antennas.

The performance metrics that we have considered are the average energy per path consumption, the overhead energy consumption rate (the percentage of energy spent for transmitting control messages) and the end to end latency.

For the numerical results, we have selected $N=25$ nodes, uniformly distributed over a square area. The nodes move around in a restricted random walk mobility model with an average speed of 5 meters/sec. The source-destination pairs of nodes are randomly chosen and the traffic burst arrival is modelled as a Poisson process with parameter $\lambda = 1$. The burst length is 64 packets and message packet length is 64 bytes. All users transmit with the same fixed power level, and for the numerical results, we have selected a path loss propagation model with propagation exponent 2. The spreading gain is selected to be $G = 128$.

Figure 1 illustrates the variation of average energy consumptions for a correct transmission of a data packet from its source to the destination. Various network densities are achieved by varying the deployment area. Given a fixed network density (25 nodes distributed in a $400 \times 400 m^2$ area), the average energy consumption with different SIR threshold values is shown in Figure 2.

From both Figure 1 and 2, we can see that using an energy related routing metric significantly reduces the energy consumption. The performance can be further improved by enhancing the underlying physical layer using beamforming. The results show that even for the traditional AODV protocol, the benefits of directional antennas are significant. Figure 1 illustrates the increase in the energy consumption with the enhanced interference level caused by a higher density network. Figure 2 shows an energy gain with the increase in the SIR threshold. This is due to a better links' quality, which yields reduced retransmissions. On the other hand, higher SIR thresholds imply fewer available links, with a negative impact

on the network connectivity, and resulting in an increased overhead for route maintenance.

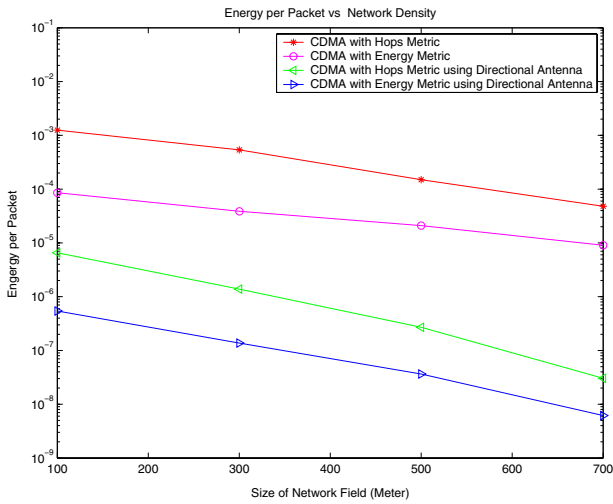


Fig. 1. Energy per Packet vs. SIR Threshold, Width of Network Area is 400m

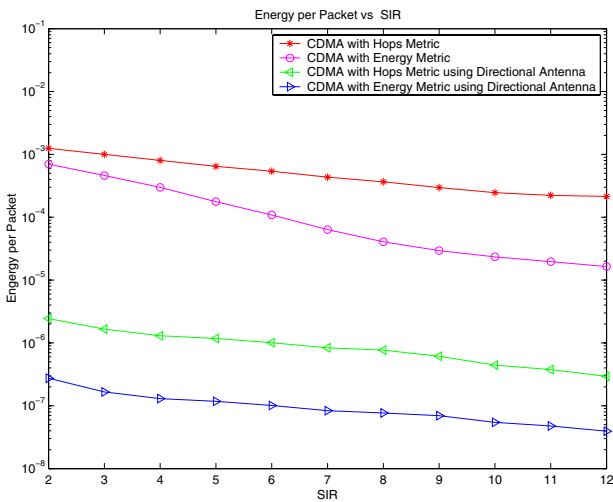


Fig. 2. Energy per Packet vs. SIR Threshold, Width of Network Area is 400m

Figure 3 illustrates this phenomenon, and shows an optimal SIR target that reduces the energy overhead for various scenarios. We defined the overhead energy ratio as the ratio of energy consumption for control messages to the total energy consumption for both control and data messages. Figure 3 also shows a substantial performance improvement for the scenarios using beamforming, especially for the high SIR threshold region, for which directional antennas significantly increases the network connectivity.

Figure 4 shows a tradeoff between the energy savings and the latency. The energy improvement is achieved at the cost of increasing the number of hops, thus resulting in a slight increase in latency. For the first two cases without beamforming, the energy metric routing gives a longer average

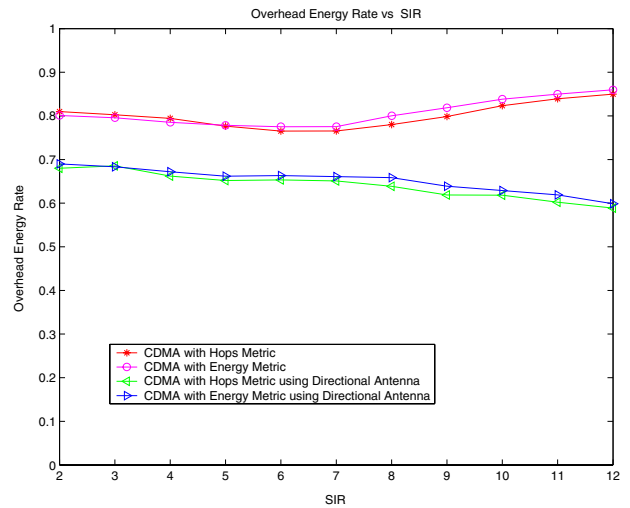


Fig. 3. Percentage of Overhead Energy vs. SIR threshold , Width of Network Area is 400m

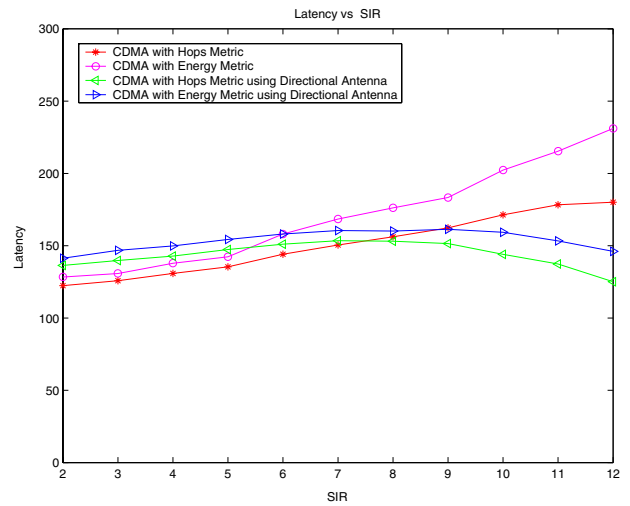


Fig. 4. End-to-End Latency vs. SIR Threshold , Width of Network Area is 400m

path length, which explains the higher latency obtained over the entire SIR threshold range. The beamforming antennas again overcome the main disadvantage of operating at high SIR thresholds, namely low connectivity for the network. The longer transmission range of the directional antennas yields a lower average hop count for the routes, and thus a lower latency. This becomes apparent for the high SIR threshold region (above 8).

On the other hand, as the SIR threshold decreases, the performance is dominated by the retransmissions caused by the lower link quality, resulting into an increased end-to-end delay. This becomes noticeable when the SIR threshold drops below 6, when the routing favors the low energy routes, at the expense of a higher hop count per route, and higher delays.

According to our simulation results, if the metric considered is the energy consumed for a correct transmission of a packet, the high SIR threshold region is the best choice for all consid-

ered scenarios. If we consider the other performance metrics, such as latency and overhead energy, the high SIR region remains a best choice for the beamforming scenarios, while the low SIR region gives better performance for omnidirectional antennas. If all performance metrics are considered, our results show that a good choice for the SIR threshold is in the range [6, 8].

VII. CONCLUSION

In this work, we have proposed an energy aware on-demand routing protocol for CDMA mobile ad hoc networks. The traditional AODV protocol was improved by both introducing an energy based routing measure, and by enhancing the physical layer performance using directional antennas. Furthermore, we have exploited the cross-layer interactions between the network and the physical layer to reduce the implementation complexity and the transmission overhead.

We have studied the performance of the proposed protocol, considering metrics such as the average energy per path consumption, the overhead energy consumption rate (the percentage of energy spent for transmitting control messages) and the end to end latency. Taking into account the above metrics, our simulation results show that an optimal SIR threshold can be selected to improve the network performance.

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