Energy Efficient AODV Routing in CDMA Ad Hoc Networks Using Beamforming

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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 provides an alternative solution of link breakage detection in traditional AODV protocol. Several performance measures are considered for evaluating the network performance, such as data energy consumption, latency, and overhead energy consumption. An optimum SIR threshold range is determined experimentally for various implementation scenarios.

1. 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. As opposed to other distance vector routing protocols, a sequence number created by the destination is used to ensure loop-free routing in AODV. There have been several studies on the performance of the 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 tight energy constraints in ad hoc networks, 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 ad hoc networks [4]. There has been significant effort in proposing energy efficient routing protocols (e.g., [5, 6]), with a more recent focus on cross-layer design solutions (e.g., [4, 7]). However, previously proposed solutions do not consider on-demand routing for mobile ad hoc networks.

In recent years, beamforming has been recognized as a breakthrough technology with 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 [8]. Moreover, a vast research literature focuses on analyzing the performance of medium access control (MAC) protocols using beamforming (e.g., [9, 10]). However, the performance advantages and the tradeoffs associated with the interactions between beamforming and AODV 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 metric and by enhancing the physical layer performance using directional antennas. In a traditional AODV routing protocol, the route with fewer hops is selected without specifically accounting for the links' quality. Consequently, data packets may be transmitted over paths with poor links, that would require more energy consumption for correct end-to-end transmission. Our proposed EA-AODV selects the route with less energy requirements, thus improving the energy efficiency. This is achieved by using an energy

aware routing metric that is tightly related to the links' quality. In the ad hoc wireless networks the poor-link quality is due to the interference introduced by other nodes which share the common transmission channel. Improvements in the physical link quality can be obtained by using directional antennas, with a direct impact on the overall energy consumption.

Compared with the traditional AODV, our EA-AODV protocol exploits the cross-layer interactions between the network and the physical layer. Next-hop information for a traffic flow obtained from routing scheme in network layer determines the intended direction of the antenna at the physical layer which ensures an energy efficient data transmission. On the other hand, the link state information detected by the physical layer helps the routing scheme to maintain the local connectivity at the network layer. This provides an alternative solution for the link breakage detection compared to the HELLO message broadcasting from traditional AODV protocols.

Signal-to-interference ratio (SIR) measured at the receiver represents an indicator of the current link quality in the physical layer. A link is considered to be in poor condition if the SIR is below a certain value. In our system, an SIR threshold is used to determine the availability of a link. Consequently, the SIR threshold value will affect the number of available links in the network and thereby the network connectivity. Our simulation results for a CDMA ad hoc network show that an optimal signal-to-interference (SIR) threshold 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.

The rest of this paper is organized as follows. In the following section, we describe the network model. We describe the proposed energy aware AODV protocol in Section 3. The next section introduces directional antennas into our EA-AODV protocol. In Section 5, simulation results show the performance of the EA-AODV protocol according to various performance metrics. A summary of performance gains for the proposed cross-layer algorithm is presented in Section 6, and conclusions are presented in Section 7.

2. 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 preset routing metric. Ad hoc on-demand distance vector routing (AODV) is used for ad hoc networks to create routes as they are needed. In this paper, AODV routing protocol is employed for route selections.

For the multiaccess scheme, we employ synchronous direct-sequence CDMA. All nodes use independent, ran-

domly generated, and normalized spreading sequences of length G. The transmitted bits are detected using a matched filter receiver. At the receiver, SIR estimates are obtained for the incoming links (e.g., [11]). CDMA is characterized by multipacket reception capability, and the transmission performance (received SIR) is softly degrading with the increased number of concurrent transmissions. Consequently, a link is considered to be available for routing, if the SIR at the receiver is above a predefined threshold. We consider that all the users transmitting at a given time may potentially interfere, based on their relative distance, and antenna gains. The quality of a link is thus measured by the achieved SIR, which should be above a certain threshold. By setting the SIR threshold sufficiently high, 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. This suggests that a higher network connectivity can be achieved for lower SIR threshold requirements. 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.

3. ENERGY AWARE AODV PROTOCOL

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 [12]:

$$E^{ij} = \frac{MP_i}{RP_c(\gamma_{ij})}, \tag{1}$$

where M denotes the length of the packet, P_i is the transmission power at node i, 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 [12] which gives

$$P_c(\gamma_{ij}) \approx \left(1 - 2\,\mathrm{BER}_{ij}\right)^M, \tag{2}$$

where BER_{ij} is the bit error rate for link (i, j). As an example, for noncoherent frequency shift keying (FSK),

$$\mathrm{BER}_{ij} = 0.5 \exp\left(-\frac{\gamma_{ij}}{2}\right). \tag{3}$$

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 [4]

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

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, we select the energy per packet on a route as a routing criterion for our modified AODV protocol.

The basic routing mechanism is described as follows. When a node S needs a route to some destination D, it will broadcast a *route request* to its neighbors. Each intermediate node forwarding the route request records a reverse route back to node S.

Once node D or a node having a route to D hears the route request, it will generate a *route reply* including the information about last known sequence number of D and the energy requirement to reach D (according to our energy aware metric and given SIR measurements for each link on the path). This route reply will be sent back along the reverse route to node S. Then, the energy requirement of each hop from S to D along this path is conveyed to S via this route reply. Different replying nodes send back their route reply individually. Among those available routes, S selects the one that has the most recent sequence number or the lowest energy requirement given the same sequence numbers.

We note that the selection of the lowest energy path is determined by the current SIR measurements for the active links on the paths, which in turn are affected by the choice of paths and beam directions for antennas (for the beamforming case discussed later on), as well as by the mobility. Therefore, the minimum energy route selection is possibly no longer optimal at the time of decision, or later on. It is extremely difficult to obtain optimal energy paths in a practical low-complexity system with mobility. This would imply continuous search for new routes as the system interference changes (mobility, new routes, antenna patterns), with a tremendous network overhead expenditure. To overcome this problem, we propose to tune the energy performance of the routing scheme via the SIR threshold parameter. More specifically, any link on the path that fails to meet the SIR threshold requirement 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 contains this broken link is disabled. A new *route discovery* process as described above is initiated to find a new route to the destination. Optimizing the value of the SIR threshold can actually optimize the energy efficiency of the routing protocol, as we will see shortly in the simulation results section.

In order to maintain routes, the classic AODV routing protocol usually requires that each node periodically transmits a HELLO message with a default rate of once per second, to detect link breakages. 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 predefined 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 (a low-quality 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. More specifically, the link state information obtained from the physical layer can be made available for the network layer to facilitate a prompt reaction to the link quality degradation.

4. DIRECTIONAL ANTENNAS IN EA-AODV

In CDMA ad hoc wireless networks, the interference between the mobile hosts leading to a lower SIR is the main cause for a high-energy consumption. 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 and signal environments. While smart antenna systems have a better performance on the rejection of interference, they require sophisticated adaptive beamforming and complex programmable digital signal processing (DSP) or field programmable gate arrays (FPGA) techniques. By contrast, simple switched beam systems have the advantage of reduced processing energy and less implementation complexity. Furthermore, switched beam systems provide a significant range extension and a considerable interference rejection capability, when the desired receiver is at the center of the beam.

In this paper, 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. It has a switching mechanism that enables it to select the beam pointing to a desired direction to concentrate the propagation energy to this particular direction. Each of the beams has a conical radiation pattern, P_g, spanning an angle of $2\pi/K$ radians with equal space [13]. The beams are assumed not to be overlapping. Starting from the 3 o'clock position, the beams are numbered from 1 to K clockwise.

In our study, we assume that the nodes in the network are able to determine the relative direction of a neighbor node. Such relative location information about neighbors may be obtained using a global positioning system (GPS). As an alternative solution, it could also be obtained by direction-of-arrival (DOA) estimation in smart antenna systems. Conventional digital signal processing (DSP) based DOA estimation algorithms, such as MUSIC [14] or ESPRIT [15], have been proven to achieve good results. The DOA estimation can be implemented at a node during the packet transmission from neighbors. To keep the location information up to date, periodic broadcasting of GPS information may be required, or periodically broadcasted beacons can be used for DOA estimation in smart antennas. Our focus in this paper is not on the localization problem, but rather we assume that

reasonably accurate information can be provided to the antenna by a GPS system or a GPS-free self-positioning algorithm, for example [16].

In this paper, 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.

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 nth 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 $|\Theta_{ij} - \Theta_n|$, $n = 1, \ldots, K$.

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 expressed as

$$\gamma_{ij} = G \frac{P_i G_{ij}(\Theta_{ij})/d_{ij}^2}{\sum_{k=1, k \neq i}^{N} \left(P_k G_{kj}(\Theta_{kj})/d_{kj}^2 \right)}, \qquad (5)$$

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 is considered having the main lobe gain g_m, otherwise the antenna is considered having the side lobe gain g_s. In this paper, we assume the antenna has a main lobe gain of $g_m = 10 \, \text{dBi}$, and a side lobe gain of $g_s = -7.4 \, \text{dBi}$. At the receiver, omnidirectional antennas are employed with a gain equal to 1.

The route discovery process is similar to the one discussed in the previous section, with the added complexity that position tracking procedures for next-hop neighbors need to be performed. The added complexity can be greatly reduced by just initiating the position updating procedure (either GPS location update or DOA estimation) only if the achieved SIR degrades below the SIR threshold. Alternatively, periodic feedback information on location increases the links' quality at the expense of increased overhead. This position tracking mechanism can be used as a first correction, in an attempt to improve the link quality with reduced overhead. If the SIR still remains below threshold, a link breakage is signaled to the upper layer, which triggers a new route discovery process. It becomes apparent that the choice of the SIR threshold influences greatly the energy performance of the system.

5. SIMULATION RESULTS

To simulate the performance of our proposed routing algorithm, we have built a simulation environment based on an AODV simulator developed for OMNET++ [17]. We have simulated four different scenarios.

(I) Traditional AODV with minimum hop routing for CDMA ad hoc mobile networks using omnidirectional antennas.

(II) Proposed AODV with energy as routing metric for CDMA ad hoc mobile networks using omnidirectional antennas.

(III) Traditional AODV with minimum hop routing for CDMA ad hoc mobile networks using directional antennas.

(IV) Proposed AODV with energy as routing metric for CDMA ad hoc mobile networks using directional antennas.

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 2, 5, 7, or 10 meters/s. Most of the plots are obtained for the nodes moving with a speed of 5 meters/s. The source-destination pairs of nodes are randomly chosen and the traffic burst arrival is modeled as a Poisson process with parameter $\lambda = 1$ burst/s. The burst length is 64 packets and the message packet length is 64 bytes. We have selected a path loss propagation model with propagation exponent 2 and the spreading gain is selected to be $G = 128$. The transmission rate at a node R is set to be 11 Mbps. All users are allowed to transmit simultaneously at a fixed transmission power of 30 dBm. For simplicity, we assume that GPS location information is available at every node. Also, to reduce the routing overhead, updates for next-hop information (ID and location) are requested only if the SIR of a current link falls below an SIR threshold. Furthermore, to increase the links performance as the nodes move around, we assume that location update information can be piggybacked on acknowledgment packets, such that the direction of the beam can be corrected.

The simulation time per run is 10^4 simulation seconds in OMNET++ simulation environment, and 100 runs are carried out to obtain average performance measures.

The performance metrics that we have considered are the average energy per path consumption, the overhead energy consumption rate, and the end-to-end latency. The average energy per path consumption is determined as the sum of transmission energy consumption per route E_r for all data packets delivered on the route, normalized by the number of delivered packets.

We also define the overhead energy consumption rate to be the percentage of total transmission energy consumption spent for transmitting control packets to establish and maintain route information. The overhead is determined as

$$\frac{E_{\text{Ctrl}}}{E_{\text{Ctrl}} + E_{\text{Data}}}, \qquad (6)$$

where E_{Ctrl} represents the total energy cost for control packets transmitted over the network and E_{Data} denotes the energy cost for data packets transmission during the simulation time. The routing control packets which are taken into account in determining the overhead energy consumption
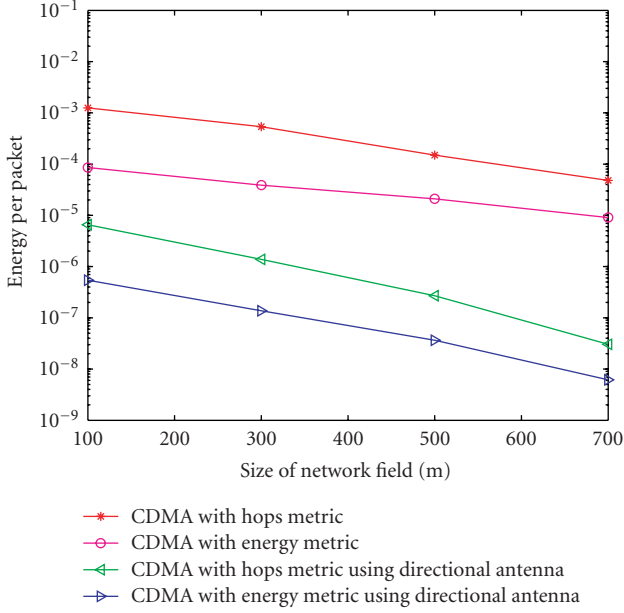
FIGURE 1: Energy per packet versus network density, SIR threshold $\gamma_{ij} = 7$, average speed is 5 meters/s.
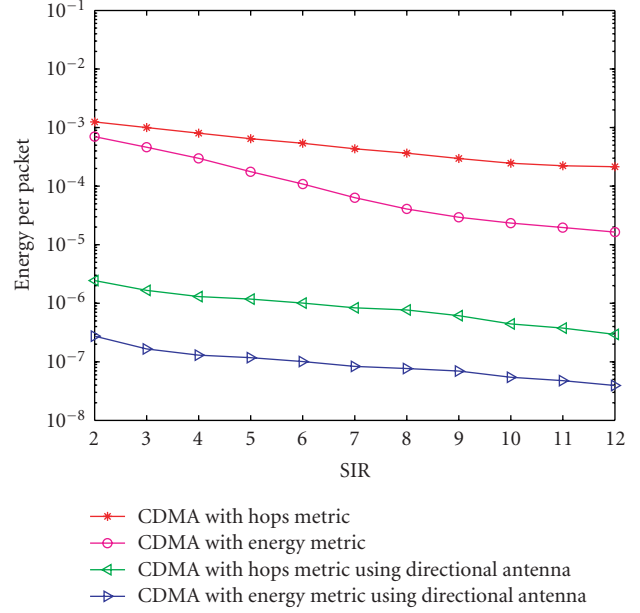

FIGURE 2: Energy per packet versus SIR threshold, width of network area is 400 m, average speed is 5 meters/s.

are route request (RREQ), route reply (RREP), route error (RERR), and route reply acknowledgment (RREP_ACK), four message types defined by AODV.

The end-to-end latency is considered as the average delay for a data packet to be delivered from its source to its destination across the network. During the simulation, we measure the latency by computing the time difference between the time stamps which are taken when a data packet departs from its source and when it arrives at the destination.

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

From both Figures 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. Increasing the SIR threshold results in better links' quality, and consequently 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.

Figure 3 illustrates this phenomenon and shows an optimal SIR target that reduces the energy overhead for various
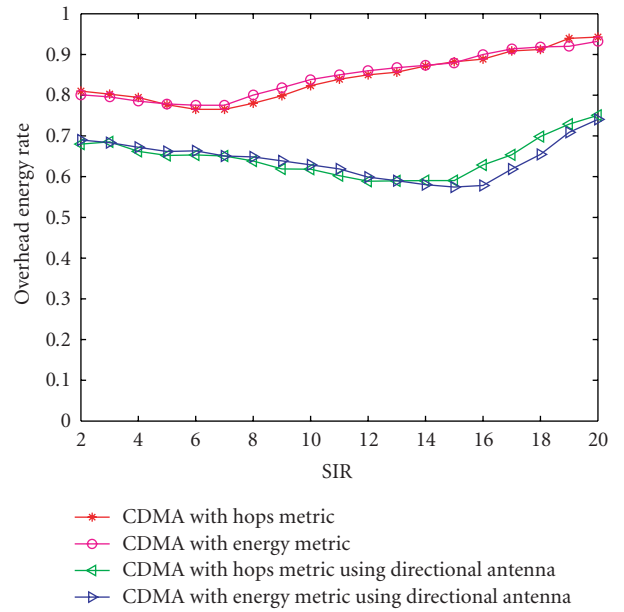

FIGURE 3: Percentage of overhead energy versus SIR threshold, width of network area is 400 m, average speed is 5 meters/s.

scenarios. We can see that an optimal SIR target value that minimizes the overhead energy can be determined: within [4, 18] range for omni-directional antennas, and within [7, 15] range for the switched beam scenario. The higher SIR threshold region obtained for the beamforming case is justified by a network connectivity enhancement achieved by using directional antennas. While all the above results were
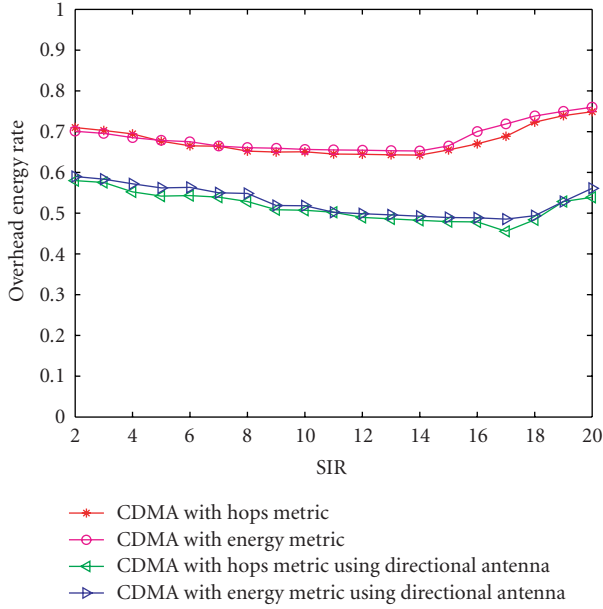
FIGURE 4: Percentage of overhead energy versus SIR threshold, width of network area is 400 m, average speed is 2 meters/s.
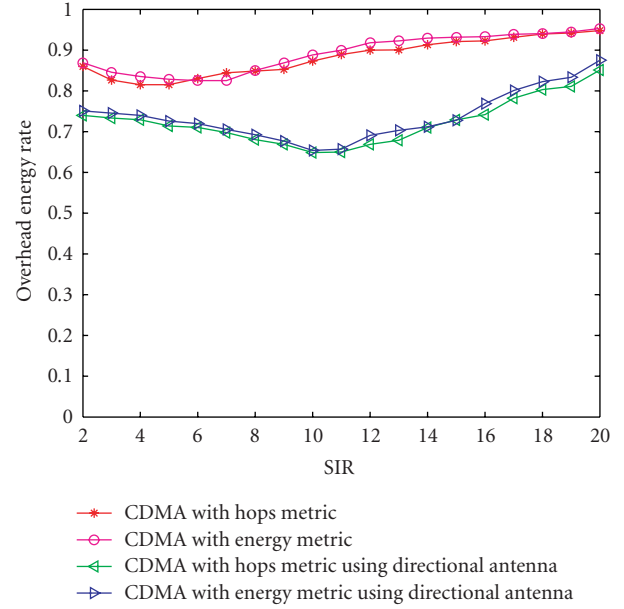

FIGURE 6: Percentage of overhead energy versus SIR threshold, width of network area is 400 m, average speed is 10 meters/s.
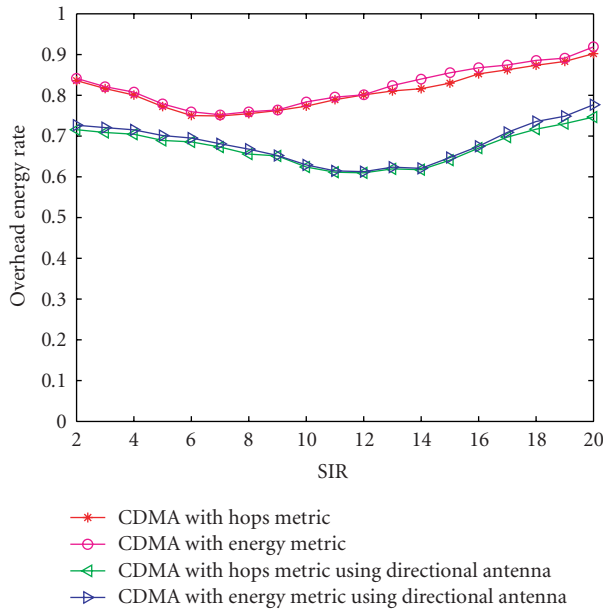

FIGURE 5: Percentage of overhead energy versus SIR threshold, width of network area is 400 m, average speed is 7 meters/s.
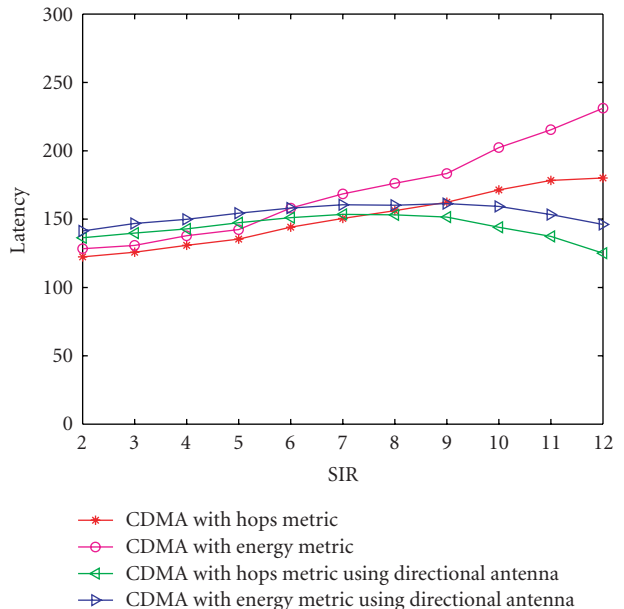

FIGURE 7: End-to-end latency versus SIR threshold, width of network area is 400 m, average speed is 5 meters/s.

obtained for an average speed for nodes of 5 meters/s, we also obtain optimum SIR points that minimize the overhead energy for an average speed of 2, 7, and 10 meters/s, respectively. Figures 4, 5, and 6 show that the optimum SIR target decreases as the mobility increases, as faster moving terminals imply a higher overhead for creating new routes, thus reducing the value of the optimum SIR threshold (a lower value will ensure that the links will be available longer).

Figure 7 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 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
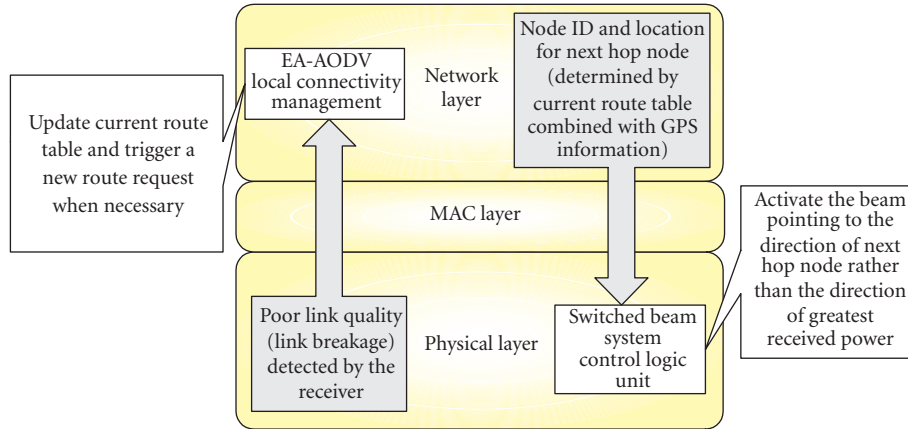
FIGURE 8: Cross-layer interactions between network layer and physical layer in EA-AODV.

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 yielding 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 considered 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 an optimal SIR threshold can be selected to improve the network performance.

6. EA-AODV: CROSS-LAYER GAINS

The energy aware AODV protocol proposed in this paper exploits the possibility of taking advantage of useful information exchange between layers to increase the system efficiency. In particular, the overhead and energy gains are obtained by using the link quality information detected from physical layer to trigger a network layer route update. This has a 2-fold advantage.

(1) It avoids the overhead and time delay associated with the HELLO packets.

   (a) HELLO packets used continuously to update information on link quality, versus SIR measurements for the link as data packets are transmitted.

   (b) An immediate notification to the network layer from the physical layer as both of the transmit-

ter node and receiver node detect a link breakage will be more breakage-sensitive than a notification that does not come up until a certain number of network layer HELLO packets are lost.

(2) Allows for energy optimization based on SIR threshold selection.

This is the focus of our simulation results: we have seen from simulation that an optimal SIR threshold can be determined to maximize the energy gains. If the link is below that threshold, a link breakage is signaled.

For the classic AODV approach, the HELLO packets are acknowledged even if received with a lower than the optimal SIR (as long as they can be correctly decoded—no energy consumption optimization is possible) leading to a higher energy overhead expenditure. Figures 3, 4, 5, and 6 illustrate the gains from using the cross-layer optimization with an optimal SIR threshold (for various mobility speeds) versus using lower than optimal link quality (for the lower SIR target region). We notice a significant gain, especially for the case that uses directional antennas.

We note that the AODV protocol can also be modified to enforce an SIR target for the acknowledgment of the HELLO packets, with similar performance results, but with the additional overhead and delay caused by notification after several lost HELLO packets. The cross-layer interactions in the EA-AODV protocol are summarized in Figure 8.

7. CONCLUSION

In this paper, 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 provide an alternative solution of link breakage detection in traditional AODV protocol and improve the energy efficiency.

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. Our experimental results have shown that the network performance depends on the SIR threshold selection at the physical layer, and an optimum SIR threshold may be selected to minimize the overhead energy in the network for various implementation scenarios.

ACKNOWLEDGMENTS

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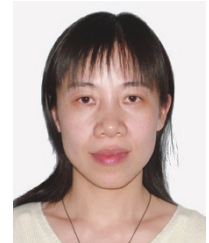
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