HWSN: Intra-Cluster Scheduling and Inter-Cluster Multi-Hop Routing Schemes to Maximize the Network Lifetime

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Abstract—

Heterogeneous wireless networks with wireless de-vices supporting multitude of radio access technologies are witnessing increasing interest from network providers and consumers alike. Energy efficiency in such networks has become an important design consideration due to the limited battery life of mobile terminals on one side, and the ever increasing operational expenses pertaining to energy expenditure on the other. In this paper, we present a routing protocol for multi–radiomulti–hop wireless networks, which aims to achieve a trade–off between energy consumption in the network and routing delay, considering both the energy consumption at the devices and the link energy costs. We also present optimum route-path selection strategies by defining a utility function to minimize the energy consumption in the network while maximizing the network lifetime. Using simulations, we verify the utility of the route-path selection strategies and the efficiency of the energy aware routing algorithm. It turns out that the proposed protocol is energy efficient in terms of path selection, with a slight compromise in the end–to–end delay.

Index Terms—

multi-hop networks, energy efficiency, routing, network lifetime, performance evaluation, battery capacity.

I. INTRODUCTION

Energy optimization has been a major concern in the design of routing protocols for multi–hop wireless networks due to the limited battery life of network nodes. As the network interfaces consume significant amount of power, considerable research has been devoted to low–power design of network protocol

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stacks to ensure the energy efficiency at the device[1][2]. The network–wide energy efficiency where a largemouth of energy is wasted in maintaining communication links and network connectivity is dealt in [3]. In multi–how ireless networks, energy efficient routing schemes main try to minimize the active communication energy required transmit and receive packets [4]. In many real–time applications, the stringent end–to–end delay requirements demand hybrid routing schemes which balance energy efficiency and QoS optimization. Moreover, transmission rates are shown to have considerable impact on the transmission delay and transmission distance, together with the transmission power, which can also influence energy aware routing mechanisms [4][5]. The heterogeneity of available

wireless interfaces at the network devices also affects the energy efficiency of the routing protocols. Localized energy optimization is not an acceptable strategy for multi–hop wireless networks equipped with multiple wireless technologies, where power consumption at the device or over a specific link is not an accurate metric to assess the overall energy efficiency from a network–wide scale for data forwarding over multi–hop links [6]. However, there are only few studies on energy-aware rout-ing for multi-radio heterogeneous wireless networks which consider the balance between QoS and energy efficiency [4][7][8][9][13]. Most of these algorithms focus on maximizing the network lifetime when dealing with route requests without latency constraints, where the network lifetime is defined as the number of messages successfully routed before the first failed message route (or the first node to fail in the network) [10][5]. Khandani et al. [11] studied minimum energy routing problem by exploiting both wireless broadcast advantage and cooperative

communications. They developed a dynamic programming based solution and two heuristic algorithms to find the minimum energy route for a single message. However, their approach is limited to individual messages as opposed to data flows. In this paper, we propose an on-demand routing algorithm tailored for multi-hop networks equipped with multiple inter-faces, where the main objective is to minimize the link energy costs and the residual battery consumption at the devices, thereby maximizing the network lifetime. Our route selection approach exploits the available network interfaces and links, and is governed by policies defined at the network level to optimize energy consumption at the nodes participating in routing packets. We combine a neighborhood aware route discovery approach with the advantages of controlled broadcast to enable the destination or the nearest dedicated node (e.g., a gateway node with a known route to the destination) to compute the route path intelligently taking into account the link energy costs and the battery capacities at the intermediate nodes. To design a balanced routing approach, we also propose different online route path selection strategies which further optimize the applicability of the proposed routing technique under varying network conditions. The rest of the paper is organized as follows. Section 2 introduces the system model and problem definition. In Section 3, we present the optimum path selection strategies that support the routing framework. Section 4 presents the proposed energy aware routing technique. Section 5 discusses the performance evaluation and finally, we conclude the paper in Section 6.

II. NETWORKMODEL

In this section, we present the multi–radio heterogeneous wireless network model that we consider in this work. Figure 1 depicts the considered network model with multi–radio interfaces between nodes and the corresponding

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energy link costs [6]. The routing strategy for this network model also cons idlers the multiple link options per node–pair (and the corresponding energy link cost) to route the packets. Note that the energy cost per link option may vary with time depending on the channel gain variation over time. In the energy aware model, we only consider the residual battery lifetime of the wireless nodes and the energy link cost related to the data transmission process. The energy link cost relates to the required power to transmit the data from a transmitter to a receiver over a distance, the corresponding data rate and the length of the information to be transmitted. Our goal is to maximize the energy efficiency in communications, pertaining to the routing of information and overhead related to maintaining the route topologies. To focus on the communication energy reduction, in our model, we consider a systemic decay of the battery capacity at the mobile nodes for energy spent on other physical and application level processes. Since our main objective is to propose a routing protocol for multi–radio heterogeneous wireless networks, the details on how to coordinate transmissions with multiple radios are beyond the scope of this paper. Therefore, we assumed that (a) MAC layer technologies are implemented independently for each interface and (b) the nodes in the network are using the common interface over the same frequency channel.

III.OPTIMUMROUTE-. PATH SELECTION STRATEGIES

The strategy to select the optimum route path is one of the crucial aspects of energy aware routing. In this section, we provide the strategies adopted in choosing the route path during the route discovery process to minimize the total energy link cost and to maximize the network lifetime. The optimization is performed by the destination node which will have all the necessary information to perform the task

(as obtained from the route discovery process). The network lifetime is maximized by considering the residual lifetime of every node participating in route discovery. Maximizing the network lifetime also implicitly means that the load balancing is achieved amongst the participating nodes because the traffic flow is distributed amongst them. Here, we define the network lifetime as the time taken for the first node to drain–out its power. In a network of wireless nodes, let K2Nbe the total number of possible route–paths from S! D for a given environmental condition at a given time, which could vary in practice with time depending on node mobility and changing
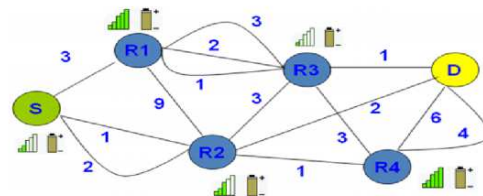

Fig. 1: Energy-aware network model considered in this work.

Channel conditions. We consider a time period where the network environment shows no significant changes during the route discover process, and as mentioned before any changes in the network are reported periodically for route maintenance after the discovery process. Let $N(k)2N$be the total number of nodes per route–path k, where k= 1;2;:::K. Furthermore, the n(k) the link and the n(k) the node in the route–path has the information metric (n;k), described by the pair $(n;k) =fE(n;k);T(n;k)g$ (1) where, n(k) = 1;2;:::N(k), the element $E(n;k)2R +$ is the energy cost for then the link in the k the path, and$(n;k)2R+$is the estimated residual lifetime (remaining lifetime) of the n the node in the path if the route is selected by the destination Das the selected route path. Note that(1;k) for all k refers to the residual lifetime of the source node itself, the knowledge of the residual lifetime of the source node is important if the destination node is required to choose the strategy to minimize the link energy cost for the first hop to increase the lifetime

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of the source node itself. It is important to note here that simultaneous optimization of the total energy link cost and the network lifetime may not be possible always since in many cases one needs to be sacrificed instead of the other that is to be traded–off. Hence we try to find a good trade-off between the two cost parameters based on some internal policies. If is the trade-off factor then we can define a utility function given by U1 (k) = N(k) X n=1 E(n;k) +1 minfT(n;k); 8n6= 1g m(2) where,0 1;8 2 R + . Then the corresponding optimum path for a given is obtained by minimizing the utility function given by, ^ k= arg min k fU1 (k)g (3)

The above optimization is basically a trade-off between selecting the minimum energy link cost route path and the maximum network lifetime as we discussed. It is important to note here that due to the differences in the orders of magnitude of the values for the first and second terms on the right hand side of equation (2) it is a challenging task to select to have a quantitative trade-off between them. In order to have an absolute quantitative trade-off we could normalize the two such that they have the same orders of magnitude approximately. At the destination, the total link energy cost can be normalized with the total energy cost for

Fig. 2: Route path selection strategy using the utility function U_1 for $\alpha = \{1.0, 0.5, 0.0\}$.

all the participating links given by, =N(k)Xn=1K Xk=1E(n;k) (4)the second term of U1(k) can be normalized with the inverse of the current network lifetime, where the network lifetime is defined as the residual lifetime of the node corresponding to the lowest residual lifetime in the

network, given by, = maxfT(n;k) 1 8n;kg (5) The utility function based on the normalized values is then given by, U1(k) = N(k)Xn=1E(n;k) 1+(1)1minfT(n;k); 8n6= 1g(6)Based on (6), now we can say that for a given value of, total energy link cost is traded–off with the network lifetime with a quantitative measure of. Note that and will change over time but such changes however would not affect the optimization process.

Figure 2 depicts the strategy related to the utility functionU1 (k) for =f1:0;0:5;0:0g, note that the cases = 0:0 and 1:0 are scaled appropriately in order to fit all the three cases (for) onto the same figure. As we observe from the figure, for= 1:0the destination node selects the route path (k= 16in the figure) corresponding to minimum energy cost regardless of the values T(n;k) for all n;k. For = 0:0on the other hand the destination node selects the route path corresponding to the path (k= 2in the figure) that has the node with the maximum lifetime of the nodes with minimum residual lifetime per path k, Finally, for = 0:5 the route path corresponding to k = 15is selected by quantitatively giving equal emphasis to the network lifetime and the total energy link cost. For the case of = 0:5we can see that the chosen path does not correspond to maximizing the network lifetime nor minimizing the total energy link cost, but tries to achieve both the requirements to some extent at the same time defined by the value .
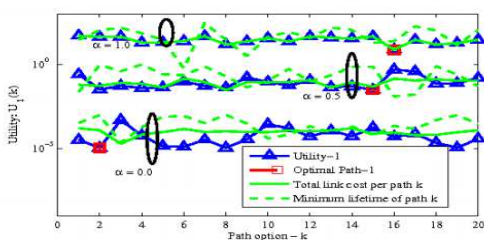
IV. ENERGYAWAREROUTING

Our energy–aware routing technique (EAR) has the objective of finding optimal energy conserving routes based on aggregated network information. EAR is based on an on– demand routing strategy where the route discovery is initiated when a node in the network has a packet to send to a destination. The routing problem is mainly to identify the most cost effective path to the nearest available gateway unless the destination is located

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locally within the multi–hope environment. Generally in on–demand routing protocols, the source node generates and broadcasts a route discovery packet (RDP) to search for a path from source to destination. The destination node upon receiving the RD Packets, uncast a route reply packet (RRP) to the source in order to set up a selected path. In EAR, we consider periodic single–hop neighborhood information exchange by every node in the network. This is a valid consideration given the cooperative behavior of wireless nodes in heterogeneous networks [6]. Secondly, unlike the on– demand approach where the destination node choosing the first arriving route request packet with minimum hop count [12], the destination node in EAR considers all the RD Ppackets received within a pre–defined time window to estimate the most energy efficient path without compromising the end–to–end path delay to ensure adequate QoS for the flows. During the route discovery process, each intermediate node piggybacks the energy related metrics (such as the remaining battery level, energy cost per bit, etc.,) as well as its identity on the RDP message and forwards the packets (re-broadcasts). The destination node receives multiple RDP packets, but chooses the best route with respect to the optimum route path selection strategy chosen by the destination (as explained in Section 3). The destination node upon receiving the first RDP packet will issue a time out period within which it will listen to and receives all the RDP packets with the respective identifier. The route discovery process and the path information aggregation approaches are shown in Algorithm.

1and Algorithm. 2 respectively. Algorithm 1Route Discovery Process

Algorithm 1 *Route Discovery Process*

```
 1: Procedure at the source node(s)
 2:  unicast(DATA : srdId, dstId, data)
 3:  if routeDb.dstId ≠ ∅ {S starts route discovery} then
 4:      unicast(DATA)
 5:      send(DATA) {S sends a data message to D}
 6:  else
 7:      buffer(DATA) {S puts the message on the buffer}
 8:      for all Interface ∈ Node do
 9:          broadcast(RDP) {S creates a query message}
10:          send(RDP)
11:      end for
12:  end if
```

The RDP packets are given a hop limit (chosen as 5 in our implementation) to introduce a restricted flooding of route discovery messages in the network. The hop limit value is determined based on the overall network size and density. Another measure to control the flooding of route discovery packets is the packet rebroadcast limit implemented to control the rebroadcast of RDP packets since the destination is already implementing a timeout period for reception of the RDP packets and it will be logical for the intermediate nodes to control the rebroadcast of RDP packets for the same flow request. The rebroadcast limit will also depend on the network size and density and the hop limit value. Such mechanisms inherently balance the traffic surge introduced by the route discovery broadcast mechanism while indirectly balancing the energy consumption at the nodes for the control packets.

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Algorithm 2 *Path Information Computation*

1: **Procedure at intermediate node(s)**
2: receive(RDP) {N receives a query message}
3: **if** $RDP.hopNb = hopLimit$ **then**
4:    delete RDP {RDP achieves the hopLimit}
5:    **return** {Terminate}
6: **end if**
7: **if** $\exists i \in rdpDb : rdpDb(i).rdpId = RDP.rdpId$ **and** $rdpDb(i).srcId = RDP.srcId$ **and** $rdpDb(i).reBr > rebrLimit$ **then**
8:    delete RDP {RDP achieved the rebroadcast limit}
9:    **return** {Terminate}
10: **else**
11:    **if** $ndId \neq RDP.dstId$ **then**
12:       $rdpDb \leftarrow rdpDb \cup (RDP.rdpId, RDP.srcId)$ {N adds new rdpDb entry}
13:       $rdpDb \leftarrow rdpDb.reBr + 1$N increases the number of re-broadcast message in 1
14:       $RDP.hopNb \leftarrow RDP.hopNb + 1$ {N increases the hopNb in 1 hop}
15:       **for all** $Interface \in Node$ **do**
16:          $RDP.uniqueId \leftarrow RDP.uniqueId[n] \cup uniqueId[n+1]$ {N appends its own uniqueId to the RDP}
17:          $RDP.lifeT \leftarrow RDP.lifeT[n] \cup lifeT[n+1]$ {N appends its own lifeTime to the RDP}
18:          $RDP.costEnrLink \leftarrow RDP.costEnrLink[n] \cup costEnrLink[n+1]$ {N appends its own link energy cost to RDP}
19:          send(RDP) {N re-broadcast the RDP}
20:       **end for**
21:    **else**
22:       tempBuffer(RDP) {N is the destination (D), D puts the message on the temporal buffer}
23:       delay($Timerseconds$)
24:       calculate($OptPathCost$) {route selection strategy}
25:       $pathRoute(k) \leftarrow uniqueId_1 \cup uniqueId_2 ... \cup uniqueId_n$
26:       unicast(RRP) {S creates a new RRP}
27:       send(RRP)
28:       $routeDb \leftarrow routeDb \cup (U)$ {U=(RDP.path, RDP.srcId, RDP.OptPathCost)}
29:    **end if**
30: **end if**

Message depending on its remaining battery capacity. When it is higher than a threshold value, the RDP is forwarded; otherwise in the case of the battery capacity dropping between secondary thresholds, the RDP will be forwarded only on the minimum power interface, and lastly upon exceeding the secondary threshold, the packet is dropped. This will ensure that the destination is receiving the RDP packets only through the best available links and through nodes with a minimum available battery capacity. Eventually, in the event of the entire network nodes below a particular threshold, to ensure that the data forwarding process is still active, the revised RDP(in case the source does not receive a route to the destination for a period of time) will be sent with a higher sequence flag to ensure

that the nodes use a revised threshold for the battery capacity. At this moment, we adopt similar route maintenance approach as in DSR [12] using the Route Error Reply (RER) packet sent to the source node upon discovery of broken links at intermediate nodes.

Algorithm 3 *Route Reply Process*

1: **Update of routeDb at the node(s)**
2: receive(RRP) {N receives a RRP}
3: **if** $ndId \neq RRP.srcId$ **then**
4:    send(RRP)
5: **else**
6:    $routeDb \leftarrow routeDb \cup (Z)$ {Z = (RRP.path, RRP.dstId, RRP.OptPathCost)}
7:    delete RDP { S drops the message}
8:    **if** $buffer \neq \emptyset$ {S has messages on the buffer} **then**
9:       unicast($DATA$)
10:      send($DATA$)
11:   **end if**
12: **end if**

V. SIMULATION RESULTS

In this section, we present the simulation results for the EAR protocol. The implementation was carried out using the OM- NeT++ [14] link level simulator to analyze the performance and comparison of the EAR protocol. We present a complete analysis of the EAR routing mechanism for different values. We considered a total of 20 fixed nodes deployed in a playground area of 300mper 300m(refer Figure 3). The transmission range and carrier sense range of nodes varying between a maximum of100and150meters for each interface. The wireless device is considered to have dual interfaces and B, and we used a transmission power between (60–80)mW for interface And (40-50)mWfor interface B. In order to send 1800unicast packets from10source nodes to 10destination nodes, the application layer sent a UDP data flow (1 packet each 1s with a packet size of1000 bytes). Therefore, the scenario has considered10data flows existing simultaneously. At the network level, we implemented two routing protocols (i) Dynamic Source Routing (DSR) [12] and (ii) Energy Aware Routing (EAR) in order to compare the network performance. The parameters used at the MAC layer are according to 802.11 and CSMA/CA

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standard protocols for interface And B respectively. Results shown in this paper are the average of 10 runs in order to present reliable results. We would like to remark that for all simulated cases the packet loss was 0%.
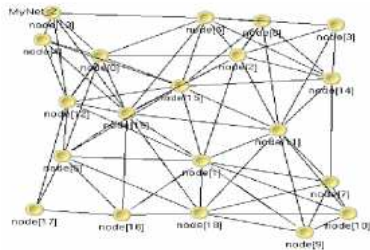
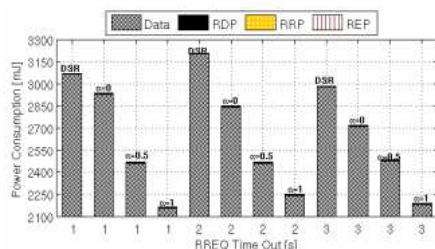

Fig. 3: Wireless scenario adopted for the simulation.

Fig. 4: Total energy consumption of the network for the DSR and EAR protocols. RREQ–time–out=(1, 2, 3)s.

Simulation measurements: Here, we report the outcome of a set of experiments using the simulation model discussed before together with the strategy related to the utility functionU1(k). Measurements have been carried out exploiting several deployment scenarios for =(1.0, 0.5, 0) and RDP–time–out=(1, 2, 3)s. By RDP–time–out, we mean the time that each destination node waits before it decides the route for the data. We fixed the hop limit to5hops. In order to evaluate the network performance for DSR and EAR protocols, we focus on metrics such as (i) total energy consumption of the network, (ii) network lifetime, and (iii) latency of each data flow. In order to collect reliable network statistics, we repeated each run for 10 times. We considered the average value for each metric reported with the respective 95% confidence interval. Firstly, Figure 4 shows the total energy consumption of the network divided into the energy consumed by the data and overhead for the DSR and EAR protocols respectively. We varied the

RDP–time–out with (1 ,2, 3)s and with (0, 0.5, 1) values in order to evaluate the effects of these values over the total energy consumption of the network. Since our objective is to evaluate the energy efficiency of the DSR and EAR protocols, the energy consumption is evaluated at the network layer assuming a unit voltage level and hence by measuring the current over time. In terms of energy consumption, the results show that EAR performs better than the DSR protocol, and the energy consumed by overhead is depreciable in comparison with the energy consumed by the data. Moreover, the RDP– time–out value has low impact on energy consumption of the network while has a higher impact on energy consumption
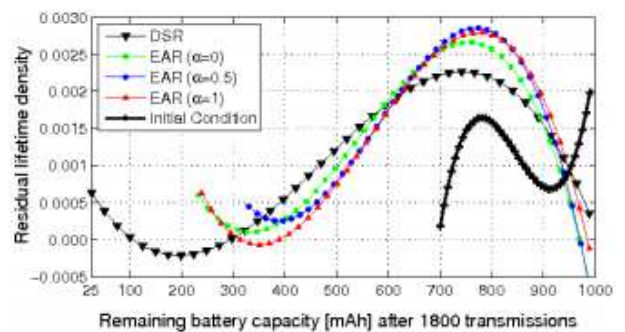

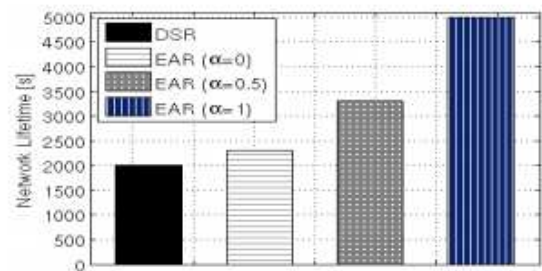Fig. 5: Residual lifetime density in the nodes for the DSR and EAR protocols.

Fig. 6: Network lifetime for the DSR and EAR protocols.

of the network as expected. To understand the impact on network lifetime, we fix the RDP–time–out value to2sbased on the results from Fig 4. The results in Figure 5 show the residual lifetime density the nodes. From the figure, the initial condition is simply the value of battery capacity at the beginning of the simulation. For the other results, the residual lifetime density was calculated using the remaining battery

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capacity in the nodes after 1800 transmissions. We can observe from the results that for EAR, the network residual lifetime density is narrower than in DSR, which means that more nodes in the network have better lifetime as we desired. Figure 6 depicts the network lifetime for DSR and EAR. By 'network lifetime', we mean the time taken for the first node to drain-out its battery. In order to calculate network lifetime value, we repeated the simulation for the same parameters for 6000packet transmissions. The results show that the network lifetime improves for all the values of compared to the network lifetime performance of DSR. Moreover, when is increased, we can see that the lifetime also improves, due to the fact that, when $6= 1$ the path selected becomes costlier than $= 1$ and hence draining nodes at a faster pace, which in
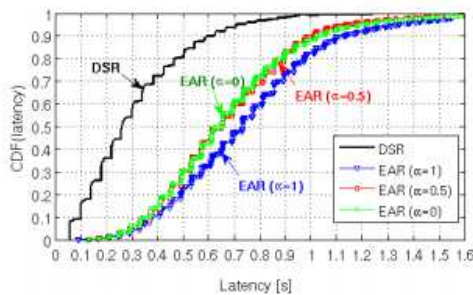

Fig. 7: Cumulative distribution function of packet latency of the data flow (node 1-4) for the DSR and EAR protocols.
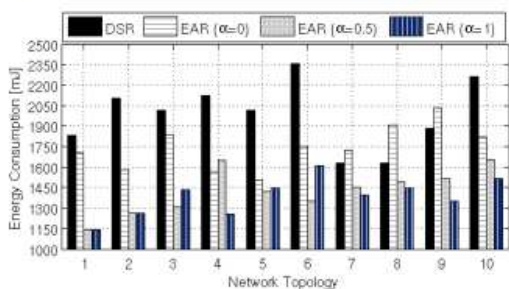

Fig. 8: Total energy consumption of the network, using 10 different network topologies, for the DSR and EAR protocols.

turn reduces the lifetime. However, when there are smaller number of nodes considered in the network with equal initial battery conditions $= 0$ shows better network lifetime results. We analyzed the latency at each route in order to quantify the difference between DSR and EAR. Figure 7 depicts the

cumulative distribution function (CDF) of the packet latency for the DSR and EAR protocols. We chose data flow between node1and4in our results since it was the worst case reported from our simulations. In terms of latency, the results show that DSR performs better than EAR while EAR protocol with= 1is the worst compared to= (0;0:5). Thus, the latencyin EAR is not comparable with that of DSR. This is justifiable hence the number of hops involved in the route path shall be significantly different from that of EAR. The results show tha the improvements in terms of energy consumption and lifetime can be made with a slight compromise in the end-to-end delay It is important to note that the curves are not smooth due to the fixed topology of our scenario. Consequently, there are fixed latency values between the nodes and thus the latency values vary around specific values. Finally, we repeated the simulation by varying the positions of the nodes randomly for the same parameters for differen network topologies. Fig 8 shows the total energy consumption of the network using 10 different network topologies for DSR and EAR. The results show that the EAR protocol is more efficient than the DSR protocol in terms of energy consumption. For the network topology number 7;8 and 9 the energy consumption in EAR protocol with $= 0$ is larger than the energy consumption with the DSR protocol. This is due to the fact that, the strategy related to the utility function U1 (k) for $= 0$ is to maximize the network lifetime rather than the energy consumption.

VI. CONCLUSIONS

We investigated the problem of finding energy–efficient routing paths to minimize the energy consumption and maximize the overall network lifetime in heterogeneous multi-hop wireless networks with multiple radio nodes. We proposed an on–demand energy aware path selection mechanism which was shown to optimize

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the energy consumption at the nodes participating in routing packets in the network. The proposed routing mechanism was evaluated under various scenarios and the results show the applicability of our algorithm in the context of multi–hop networks with multiple interfaces which can help the participating nodes in optimizing their energy performance. Moreover, the path selection strategies were evaluated for their utility in the context of energy–aware routing. Finally, the results show that EAR performs around 30%–50% better than the DSR protocol in terms of energy consumption and lifetime. We are currently evaluating multiple path selection strategies and their influence on the different routing approaches to identify the trade–offs with the choice of the policies and deciding parameters in choosing route paths. Because,the choice of the value may be an interesting topic for better performance of the proposed routing protocol. Moreover, we are currently extending the EAR approach to mobile network scenarios in order to investigate the correlation between the route maintenance measures and the route path selection strategies in mobile environments.

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