DELAR: Device/Energy/Load Aware Relaying in Heterogenous Wireless Ad Hoc Networks

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ABSTRACT

Energy conservation is of great importance for mobile ad hoc networks in which most nodes are equipped with limited energy sources. In this paper, we propose a novel device/energy/load aware relaying scheme (DELAR) for heterogeneous mobile ad hoc networks, where some nodes, called P-nodes, are powered by powerful external or renewable energy sources. In DELAR the heterogeneity of nodal energy capabilities or device types, nodal residue energy information, and nodal load status are nicely incorporated into established routing protocols with the aim of prolonging the network lifetime as much as possible. In addition, we also resolve the rather challenging issue of how to support the MAC-layer acknowledgements in the presence of unidirectional links caused by asymmetrical power capabilities. Unlike other schemes that resort to outband channels or higher layer solutions when facing this problem, we propose an Asymmetric MAC (A-MAC) as an elegant solution. Taking full advantage of P-nodes, DELAR can significantly prolong the network lifetime; meanwhile, it strikes a good balance between power efficiency and the overall system performance. Moreover, our scheme operates in a distributed manner and is easy to implement. Detailed simulation study is carried out to justify and validate the effectiveness and efficiency of our scheme.

I. INTRODUCTION

The realistic deployment of mobile ad hoc networks faces lots of challenges, one of which comes from the finite energy supplies of mobile nodes. Since most nodes are usually battery-supplied, once a node depletes its energy, it will become useless. Some adverse consequences of this node diminution include degradation of network performance and unfavorable network partition. Thus how to prolong the network lifetime as much as possible becomes a crucial issue for mobile ad hoc networks. To improve the power efficiency, in recent years many efforts have been made

at the MAC and network layers. Several energy-efficient MAC protocols, including PAMAS [1], S-MAC [2], and the schemes presented in [3], are proposed to efficiently and intelligently control nodes' sleep and wake schedules. In addition, PCM [4] uses different transmission power levels for RTS/CTS and DATA/ACK frames on a per-packet basis. On the other hand, extensive research has been carried out at the network layer as well, which can be classified into two main categories: energy-aware routing and topology or power control. In [5]–[8], several power-aware metrics are presented and incorporated into routing protocols to improve the power efficiency. The rationale behind the category of power or topology control [9]–[15] is to control nodes' transmission power so that a desirable topology or connectivity can be maintained for saving energy. Moreover, PARO [16] is another notable approach designed for scenarios where nodes can dynamically adjust their transmission power and adopt forwarding routes with longer hops.

Most of previous proposals, however, only consider homogeneous networks in terms of energy supply, where mobile nodes are assumed to have the same and limited energy capabilities. In contrast, we consider a more realistic type of networks in which, in contrast to battery-powered nodes, there are some powerful nodes (P-nodes) having almost unlimited energy supplies such as solar cells. Communication devices installed on a mobile vehicle and powered by inside alternators are examples of such P-nodes. How to take full advantage of such P-nodes so as to prolong the network lifetime as much as possible is a rather interesting problem and has not been well addressed yet. Perhaps the closest work to our own can be found in [17], where a battery-powered node always forward its packets to a nearby P-node even if it may consume lots of energy to do so, and the P-node will forwards the packet with allowed maximum transmission power to the destination or another routing terminal that is a P-node in most cases. Their scheme is suitable for the scenarios where there are lots

of P-nodes. In our previous work [18], we considered the overall energy used for transmitting a packet and proposed a device and energy aware routing protocol (DEAR) to better utilize the P-nodes. Based on the assumption that a P-node can raise its transmission power to reach any node in the network at any time, DEAR uses a redirection table to decide whether a battery-powered node should redirect a packet to a P-node and request the P-node to finish the last hop delivery, or just adopt the typical minimum energy route without any help from P-nodes. However, DEAR uses a separate channel to notify all other nodes to stop their ongoing transmissions when any P-node needs to transmit a packet, which might result in degradation of network performance. In addition, DEAR does not address how to provide MAC layer acknowledgements to P-nodes in the the presence of unidirectional links, since the P-nodes may produce temporary unidirectional links due to asymmetrical power capabilities. To tackle the problems with DEAR, we propose a novel cross-layer designed device/energy/load aware relaying scheme (DELAR) to make full use of the P-nodes. In addition, we propose an Asymmetric MAC (A-MAC) protocol to support the transmission of MAC layer acknowledgements on unidirectional links.

The rest of the paper is organized as follows. In Section II, we elaborate DELAR from the system model to the network layer component, and then to the MAC protocol, i.e., *A-MAC*. In Section III, we evaluate our DELAR scheme through simulations. Finally, we summarize this paper and outline our future work in Section IV.

II. DEVICE-ENERGY-LOAD AWARE RELAYING

A. *Overview OF DELAR*

As mentioned before, we focus on heterogeneous networks in this paper, where there are two kinds of wireless devices powered by different energy supplies, namely, outlet-powered nodes (called P-nodes hereafter) and battery-powered nodes (called B-nodes hereafter). In the literature there are quite a few power or topology control schemes for maintaining time-varying transmission power. However, to reduce the related maintenance overhead and to make our scheme easily implementable, we assume that any B-node i can maintain a circular transmission range BTR_i (basic transmission range) before draining its energy. And for the ease of presentation, we assume that all the B-nodes have identical BTRs, though our DELAR can be readily extended to the case of different BTRs. In addition, we assume that P-nodes are able to boost their transmission power and hence cover larger areas than B-nodes. In practice, P-nodes may have different maximum transmission ranges as a result of the difference in antenna sizes and types, and even energy supplies. Again, for reasons of brevity only,

we assume that all the P-nodes have identical maximum transmission range of $PTR_{max} = M \times BTR$, where M is a positive integer greater than 1. We also assume that single channel is used, i.e., all the nodes in the network share the same wireless channel. However, DELAR is applicable to multiple channels as well.

From the experience with implementing the DEAR protocol, we notice that, instead of granting them unlimited privileges of reaching any node at any time at will, it is better to limit P-nodes' maximum transmission power and their transmission activities to reduce the collisions with other ongoing transmissions. To achieve this purpose, we divide time into equal length time periods called *Super Frames*, in which some intervals are exclusively used by P-nodes, while the rest are shared by all the nodes in the network. More specifically, during one cycle of the *Super Frame*, there is a *P-to-P Period* with length t_{pp}, in which only P-nodes communicate with each other and maintain transmission range $TR_{pp} = m \times BTR, 1 < m \leq M$, while other B-nodes keep silence. Additionally, during one cycle of the *Super Frame*, each P-node has its own exclusive period called *P-to-B Period* with length t_{pb}, in which it can boost its transmission power to cover a range of $TR_{pb} = n \times BTR, 1 < n \leq M$. The rest of one cycle of the *Super Frame* is called as *B-to-B period* with length t_{bb} and is shared by all the nodes in the network. Obviously, all the P-nodes should act as other B-nodes in the *B-to-B Period* by limiting their transmission range to $TR_{bb} = BTR$. In order to make use of the P-nodes as much as possible, usually m is greater than n. During the *P-to-P Period*, only P-nodes contend the channel and communicate with other P-nodes; during a *P-to-B Period*, only the P-node owned this period can initiate transmissions without contending for the channel; during the *B-to-B Period*, all the nodes in the network can contend for the channel and initiate a transmission. While in other two periods, some contention-based MAC protocols such as the IEEE 802.11 can be used, in a *P-to-B Period* some enhanced MAC protocols should be used, because the P-node owning this period and the B-nodes it intends to communicate have different transmission power, which cause temporal asymmetrical links between the P-node and the B-nodes. Our proposed Asymmetric MAC protocol *A-MAC* is used to support RTS/CTS/DATA/ACK exchanges on the asymmetrical links. Moreover, the heterogeneity of nodal devices, and the residue energy and the load status of each node are incorporated into the routing information and propagated in the network to build routing tables. Once generating data, or residing in the forwarding path and receiving a forwarding request, a node will send out the data at an appropriate time period to the next hop in its
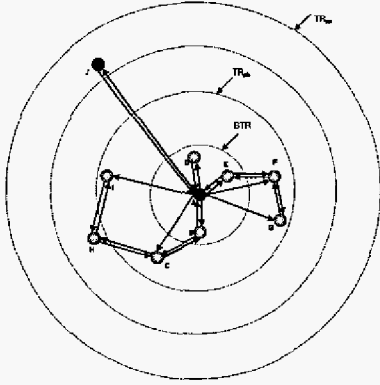
Fig. 1. An example of the neighbor choosing process.

own routing table. More specifically, when the next hop is in its TR_{bb} range, it can only forward the data during the *B-to-B Period*. While for a P-node, if the next hop is another P-node locating in this P-node's TR_{pp}, the P-node can forward the data to the next hop in the *P-to-P Period*. If the next hop is a B-node locating outside the P-node's TR_{bb} but inside its TR_{pb}, the P-node can only forward the data to the next hop in its own *P-to-B Period*. In all, with such time division scheduling and a device/energy/load aware routing metric, we expect to reduce collisions and interference to a minimum level, and utilize those P-nodes as much as possible in an efficient and cautious manner, so that we can simultaneously achieve the expected energy conservation and maintain good network performance.

The above seemingly simple operations of DELAR pose several research challenges. Given a B-node (P-node) X situated in a P-node $P's$ TR_{pb} (TR_{pp}), for instance, what criteria should the P-node P adopt to decide if this node X is a neighbor (in one hop range) or not, i.e., forwarding a packet to this node X in a one-hop manner or a multiple-hop manner? What kind of routing metric should we adopt to reflect the heterogeneity in device types, nodal energy capabilities, and local load status when setting up routing paths? How could we divide time into *Super Frames*, and how could one P-node register a *P-to-B Period* without conflicting with others' *P-to-B Periods*? For a next hop node X (a B-node) in $P's$ routing table lying outside $P's$ $TR_{bb} = BTR$ but inside its TR_{pb}, how could X send the MAC layer acknowledgements back to P in the presence of asymmetrical links resulting from the transmission power asymmetry? The remainder of this paper will address these questions in more detail.

B. P-nodes' Neighboring Criteria

In this section, we will first discuss how a P-node decide if a B-node is its neighbor. In the literature two nodes are usually considered as neighbors of each other only if they are one hop away, however, in heterogeneous networks, we have to change this criteria to cope with the existence of the P-nodes whose transmission ranges are much larger than those of the B-nodes. In this case, any node in a P-node's TR_{pb} could be a *neighbor candidate* of it. Nevertheless, in order to support the MAC layer acknowledgements, not all the candidates can be finally chosen as *neighbors* or next hops in the routing table. Before giving out the rules that guide P-nodes to make correct decisions, we first introduce the notions of *Forward Path* and *Backward Path*. For any node pair s and t, a *Forward Path* indicates the path derived from normal routing tables. For example, the *Forward Path(s, t)* can be represented as $s \rightarrow N_1 \rightarrow ... \rightarrow N_k \rightarrow t$, where $\{N_i\}$ ($1 \leq i \leq k$) denote the k intermediate nodes between s and t. For a given P-node P and any B-node X locates in $P's$ TR_{pb} range, the *Backward Path(P, X)* is defined as the *minimum-hop Forward Path(X, P)* when all the other nodes have the same BTR range. We should note that the *minimum-hop Forward Path(X, P)* is not necessary the same as the *Forward Path(X, P)*. Although *Forward Paths* are defined for any node pairs in the network, *Backward Paths* are only valid between any P-node and other B-nodes situated in its TR_{pb} range. Furthermore, for any *neighbor candidate* X of a given P-node P, this B-node X can be considered as $P's$ *neighbor* only when the *Backward Path(P, X)* satisfies the following criteria: All the intermediate nodes along the *Backward Path(P, X)* should be in $P's$ TR_{pb} range. To put it differently, a *neighbor candidate* X can be consider as a P-node $P's$ *neighbor* if and only if all the intermediate nodes along the *Backward Path(P, X)* are $P's$ *neighbors* as well.

The remaining issue is how to set up these *Backward Paths*. A simple way is to let a P-node broadcast a query message with certain transmission power, i.e., covering all the B-nodes in its $TR_{pb} = n \times BTR$ range. Once seeing such a query, each node broadcasts a special reply with the TTL value $2n$ and each node will append its own ID when relaying such special replies. The querying P-node will wait some time until collecting enough replies. A reply initiator would be considered a neighbor only and only if the querying P-node also receives replies from all the relaying nodes of its reply. We need to point out that, even when a P-node, say P_1, receives a query message initiated by another P-node, say P_2, P_1 should reply like other common B-nodes with a transmission range of BTR. Since our scheme is targeted for networks with low or moderate mobility, P-nodes can execute this process infrequently or when topology changes are detected by the MAC protocol in their respective *P-to-B Periods*. Therefore, the resulting overhead is acceptable.

In addition, P-nodes also need to exchange information

with each other to determine the neighboring relationship among them. To achieve this, during the *P-to-P Period* a P-nodes may send out a query with certain transmission power to cover a range of $TR_{pp} = m \times BTR$, and P-nodes receiving this query may send reply directly back to this requesting P-node.

Fig. 1 gives an example of the choosing-neighbor process. Suppose A is a P-node with $TR_{pb} = 2 \times BTR$ and $TR_{pp} = 4 \times BTR$, and the Backward Paths for *neighbor candidates* C, D, G and I are $C \rightarrow B \rightarrow A$, $D \rightarrow A$, $G \rightarrow F \rightarrow E \rightarrow A$, and $I \rightarrow H \rightarrow A$, respectively. Since node H does not initiate an reply to A, only C, D, and G are considered as $A's$ *neighbors*. Of course, B, E, and F are $A's$ *neighbors* as well. In this example, another P-node J is also a neighbor of node A because J is in $A's$ TR_{pp}.

C. Routing Component of DELAR

In homogeneous ad hoc networks a node can only communicate with nodes in its BTR range, while in heterogeneous ad hoc networks, a P-node is able to reach more nodes in a larger range. Therefore, the resulting topologies and routing strategies may be quite different from those in homogeneous networks. For instance, a network topology without P-nodes is depicted in Fig. 2.a, where all the links are bi-directional and labelled with equal or unequal costs. In contrast, if one node, say A, is identified as a P-node who can reach much further in the network, more unidirectional links may be added as shown in Fig. 2.b. And we label unidirectional links from P-node A to its neighbors with a cost 0 to represent node $A's$ unique power capability.

To cope with such heterogeneous networks, we require each P-node to maintain an internal neighbor table recording its chosen neighbors within the TR_{pb} and the corresponding *Backward Paths* toward those neighbors. In addition, each node in the network, including both P-nodes and B-nodes, needs to maintain a forwarding routing table similar to that in an established table-driven routing protocol for MANET. Let's define $\beta = residue\_energy(i) - \mu \times buffer\_len(i)$, the device-energy-load aware (*DELAR*) routing cost metric we adopt is defined in Eq. 1, though other cost metrics are applicable in our DELAR as well.

$$cost(i) = \begin{cases} 1/\beta, \beta > 0 \\ a, \quad \beta \leq 0 \end{cases} \quad (1)$$

In the above cost metric, α and μ are two parameters used to control the weight of the awareness of load and energy in the overall cost metric. In addition, to represent a P-node's unique power capability or device type, a P-node assume a zero cost, instead of using Eq. 1, toward its B-node neighbors within TR_{pb} or P-node neighbors within TR_{pp}. The routing information exchange proceeds according to

a. Topology in Homogeneous case
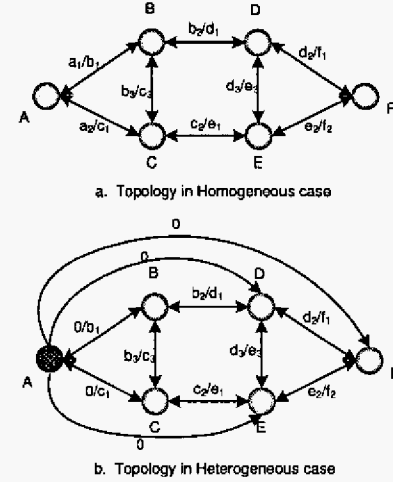
b. Topology in Heterogeneous case

Fig. 2. The topology in homogeneous and heterogeneous cases.

the adopted routing protocol. After that, a node can employ established shortest path algorithms to decide the next hops and the related costs towards all the other nodes in the network. (Here the path cost is defined as the sum of the cost metrics in Eq. 1 of all the B-nodes along a forwarding path excluding the source and the destination).

We can see that, by choosing the proper values of α and μ, the cost function defined in Eq. 1 can help prolong the network lifetime by distributing the traffic more evenly throughout the network, avoiding the overuse of a small set of nodes, and consuming nodal energy resources in a more balanced manner. Moreover, our DELAR scheme spontaneously incorporates P-nodes' unique power capabilities or device types, residual energy information, and local load statuses into the routing protocol without using the redirection tables in DEAR any more.

D. Transmission Scheduling and Super Frames

As we briefly described in Section II-A, in order to reduce the interference a P-node's communications imposed on other ongoing transmissions, it is reasonable to limit a P-node to boost their transmission power in some exclusively reserved periods. For this purpose, we divide time into equal length time periods called *Super Frames* in which each P-node is assigned an exclusive small interval, called *P-to-B Period*. In addition, a P-to-P period is allocated to allow P-nodes communicate with each other if they are within each other's TR_{pp} range. Therefore, as shown in Fig. 3, a P-node has three phases in each *Super Frame*, namely, the P-to-P Phase in which the P-node can raise its power to cover a TR_{pp} range and only communicate with other P-nodes, the P-to-B Phase in which the P-node can raise its power to cover a TR_{pb} range, and the B-to-B Phase in which the P-node acts like a B-node and
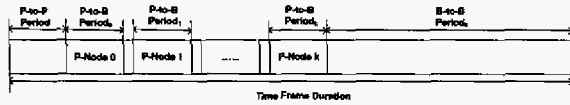
Fig. 3. The structure of a Super Frame

transmits packets to a node within its BTR. We further require a P-node only transmit packets to B-nodes outside its BTR range in its own *P-to-B Period*. We also want to note that the *B-to-B Period* is shared by all the nodes in the network. Therefore, packet scheduling is needed at a P-node to determine the appropriate transmission time of the packets to be relayed or initiated by itself. Fig. 3 gives an instance of a *Super Frame* structure including multiple reserved periods. The one-minislot-length padding between two consecutive periods is used to further reduce the interference. In our current design, one *P-to-B Period* is not allowed to shared by multiple P-nodes for simpleness. However, if perfect scheduling among P-nodes is available, we could allow this *P-to-B Period* reuse among P-nodes far away from each other. Though our scheme only needs loose synchronization and the communications between p-nodes can facilitate such synchronization, in this paper we assume that we have perfect synchronization and leave the synchronization problem as our future work.

E. Asymmetric Media Access Control Protocol (A-MAC)

The stop-and-wait ARQ scheme employed in current contention-based MAC protocols works well with bidirectional links; however, with unidirectional links, the receiver has no way to directly send the acknowledgements to the transmitter, which means that the transmitter would continuously transmit the same frame no matter whether the receiver has received it or not before timeout. Fortunately, we can make use of the aforementioned *Backward Paths* and the following *mini-routing* method to tackle this problem in an elegant way.

In many MAC protocols such as the IEEE 802.11, a receiver can only transmit an acknowledgement frame to its one-hop-away transmitter. With the cross-layer design methodology, we introduce a new concept of *mini-routing* into the MAC layer, which requests intermediate nodes to relay the receiver's acknowledgement frames, i.e., CTS/ACK frames, along the established *Backward Path(transmitter, receiver)* in a multi-hop fashion to the transmitter (a P-node) at the MAC layer. Here the routing information is no longer exclusively used by the network layer but shared by the MAC and network layers. In what follows, we describe our *A-MAC* protocol used to meet the above objectives.

Based on the IEEE 802.11, we introduce into *A-MAC*

four special frames: P-RTS, P-CTS, P-DATA, and P-ACK, all of which can only be transmitted in the *P-to-B Period*. When the P-to-B Period of a P-node comes and it happens to have some packets to transmit, it first boosts its transmission power to cover the range of $TR_{pb} = n \times BTR$. With the scheduling describe in Section II-D, all the other nodes should refrain from initiating a transmission and temporarily cannot transmit usual frames, i.e., RTS/CTS/DATA/ACK. The P-node associating with this P-to-B period can send packets to any neighboring B-node in the range of TR_{pb} with P-RTS/P-CTS/P-DATA/P-ACK exchanges.

Next, we illustrate the *A-MAC* procedures using Fig. 4, where we assume $n = 2$ and P-node A intends to send a packet to its B-node neighbor C. The location relationship among A, B, and C is also depicted in Fig. 1. First, A sends the P-RTS with $TR_{pb} = 2 \times BTR$ containing the *Backward Path(A,C)*. Then according to the length of the *Backward Path(A,C)* in this example, A sets its waiting timer for the P-CTS to be $2(SIFS + T_{P-CTS} + T_{prop})$. After receiving the P-RTS destined for it, after a *SIFS* node C will send to node B a P-CTS including the addresses of A and its own. For node B, when receiving the above P-RTS, it starts a timer equal to $SIFS + T_{P-CTS} + T_{prop}$ according to its order in the *Backward Path*. Once receiving a P-CTS from node C before timeout, B simply appends its address and relays the modified P-CTS to the P-node A. Otherwise, node B sends a P-CTS containing its own address to A after the timer expires. Before timeout, if node A does not receive any P-CTS or receives a P-CTS from node B only has B's address, it can retransmit the P-RTS until reaching a admissible number of retries. If the same situation happens, node A temporarily saves this packet for future transmission and switches to another packet with a different destination. When A successfully receives a P-CTS from B with both B's and C's addresses, the P-RTS/P-CTS exchange finishes. After a *SIFS*, A can send a P-DATA frame to node C and set the timer to $2(SIFS + T_{P-ACK} + T_{prop})$. Then the similar procedures apply. After receiving the P-ACK from node C relayed by the intermediate node B, the P-node A can start transmitting a new packet after a *DIFS* in the same manner. When its *P-to-B Period* expires, A enters the B-to-B Phase and acts as a B-node.

Besides the well-known hidden/exposed terminal problem, the purpose of our P-RTS/P-CTS is also to eliminate possible errors resulting from stale routes or nodes' mobility. For example, in the above example, if node C moves out of P-node $A's$ $2 \times BTR$ range while B is still in $A's$ BTR range, node C will not hear the P-RTS from node A and hence A could only receive from node B a P-CTS including only $B's$ address. In this case, A will think that
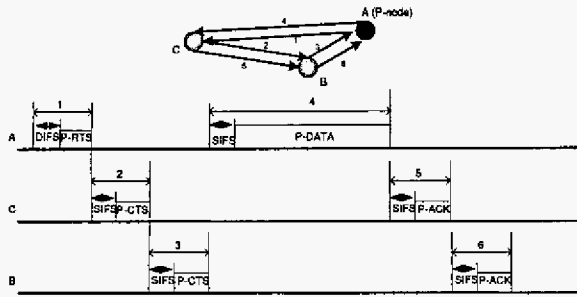
Fig. 4. The A-MAC procedure

node C is currently unreachable and may temporarily save the packets to C for future transmissions. Another situation may happen that node C is still in $A's$ $2 \times BTR$ range while node B moves out of $A's$ BTR range, in which case the P-node A will delete node C from its neighbor table. Moreover, when node C moves into $A's$ BTR range, A will receive a P-CTS from C directly. Hence, A can optimize the future transmissions to C without the help from node B any more.

III. PERFORMANCE EVALUATION

In order to evaluate our DELAR, we implemented our scheme consisting of the routing layer and the *A-MAC* in the OPNET Modeler [21]. We simulate a network with 50 nodes randomly deployed in a $1500 \times 300m^2$ area. The BTR is $250m$ and the transmission rate is $1Mbps$. In our simulation all the nodes are capable of moving in the network according to the random Waypoint mobility model [22]. There are 20 CBR data sessions between randomly selected sources and destinations, and each source generates 2 data packets with 512 bytes in length per second. In our simulation, B-nodes have the same initial energy reservoir $6kJ$. In our simulation the transmission power and reception power of B-nodes are $1560mW$ and $930mW$, respectively [23].

In our implementation we choose $m = 4$, $n = 2$, $t_{pp} = 0.1s$, $t_{pb} = 0.1s$, and $t_{bb} = 0.3s$. We simulate the network with 3 or 4 P-nodes. We compare our DELAR with the one referred to as *EAR* that has knowledge of the existence of P-nodes, in that it use the cost metric define as Eq. 1, but with only BTR and without *A-MAC*. We compare them in terms of the average energy consumption for delivery a packet from the source to the destination (not include the energy for routing purpose), the packet delivery ratio, and the packet end-to-end delay. Each run is executed for 900 seconds of simulation time with different mobility.
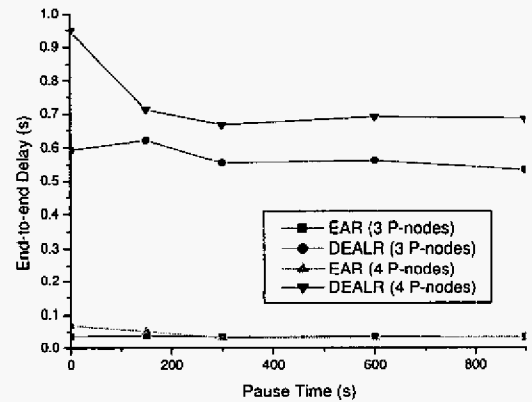
We present the simulation results in Fig. 5. The Fig. 5(a) shows the average energy consumption. As expected, compared with EAR, average energy consumption of DE-LAR is much less. These energy savings can be attributed
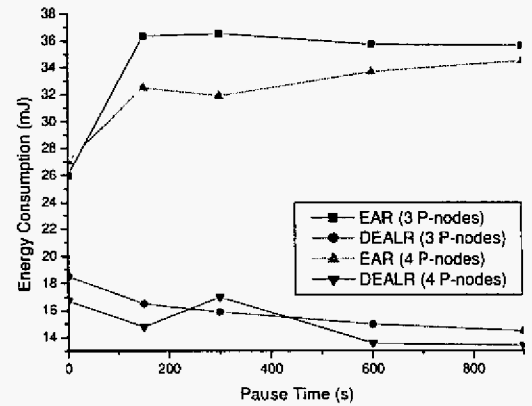
(a) Energy Consumption
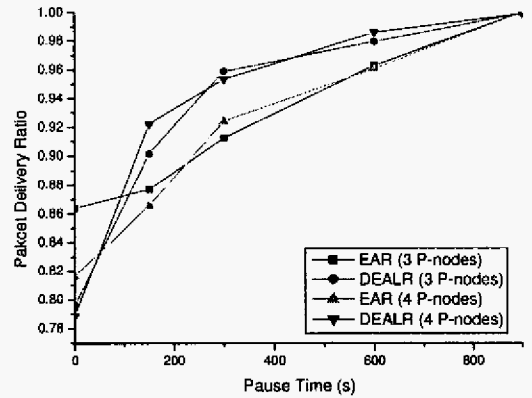
(b) Packet delivery ratio

(c) Packet end-to-end delay

Fig. 5. Simulation results

to our well scheduled transmissions and adopting different transmission power in different periods, so that P-nodes can be utilized as much as we can. We also observe that, the more power nodes exist in the network, the more energy savings we can expect.

Fig. 5(b) and Fig. 5(c) show the system performance of different approaches. We observe that our DELAR has comparable packet deliver ratio to EAR with no mobility, and outperforms EAR with moderate mobility. The reason for such phenomena is that the utilization of P-nodes shortens the hops a packet may travel, thus reducing the negative influence coming from nodal mobility. Since DELAR divides the time into super frames to schedule the transmission activities rather than contending for transmission all the time, and usually a packet needs to be buffered at a node waiting for the coming of a proper transmission period, the packet end-to-end delay of DELAR is longer than that of EAR. And with the increase of the number of P-nodes, the delay of DELAR gets longer for the reason of scheduling. Obviously, the setting of t_{pp}, t_{pb}, t_{bb} and the number of P-nodes in the network jointly affect the overall system performance. Thus a tradeoff between energy conservation and overall system performance should be well stricken by choosing proper values of the above parameters.

Through the simulations, it is shown that, DELAR is viable and effective to save energy and maintain good system performance even with only a few P-nodes in the network. Moreover, our *A-MAC* works well and is able to support the acknowledgements on unidirectional links.

IV. CONCLUSION AND FUTURE WORK

In this paper we proposed a cross-layer designed device-energy-load aware relaying scheme DELAR to utilize the heterogeneity of node power capability in wireless ad hoc networks. To make use of such heterogeneity DELAR schedules transmission activities into different periods and uses different transmission power in different periods. To support the link level acknowledgements with unidirectional links, we introduced the "mini-routing" and proposed an Asymmetric-MAC (*A-MAC*). We demonstrated that the *A-MAC* can effectively provide the MAC layer acknowledgements in the presence of unidirectional links. To our knowledge this is the first paper trying to approach this problem at the MAC layer, while other approaches try different perspectives [19], [20]. Through simulations, we demonstrated that DELAR can significantly reduce the energy consumption and thus prolong the network lifetime even with a few P-nodes existing in the network. More exploration is needed to study the relationship between the overall performance and the number of P-nodes in the network, the value of m and n, the length of P-to-P period,

P-to-B Period, and B-to-B Period.

REFERENCES

[1] S. Singh and C.S. Raghavendra, " PAMAS-Power aware multi-access protocol with signaling for ad hoc networks," *Computer Communication Review*, 28(3), 5-26,1998.

[2] W. Ye, J. Heidemann, and D. Estrin, " An energy-effcient MAC protocol for wireless sensor networks," *INFOCOM 2002*.

[3] Y.-C. Tseng, C.-S. Hsu, and T.-Y. Hsieh, " Power-saving protocols for IEEE802.11-based Multi-hop Ad Hoc Networks," *INFOCOM 2002*.

[4] E.-S. Jung and N. Vaidya, " A Power Control MAC Protocol for Ad Hoc Networks," *Mobicom 2002*.

[5] S. Singh, M. Woo, and C.S. Raghavendra, " Power-aware routing in mobile ad hoc networks," *Mobicom 1998*.

[6] C.K. Toh, " Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks," *IEEE Communication Magazine*, June 2001, pp. 138-147.

[7] J.-H. Chang and L. Tassiulas, " Energy conservation routing in wireless ad-hoc networks," *INFOCOM 2000*.

[8] S. Banerjee and A. Misra," Minimum energy paths for reliable communication in multi-hop wireless networks," *MobiHoc 2002*.

[9] V. Roodoplu and T.H. Meng, " Minimum energy mobile wireless networks," *IEEE JSAC*, Vol. 17, No. 8, pp. 1333-1344, August, 1999.

[10] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris, " Span: an energy-efficient coordination algorithm for topology maintainence in ad hoc wireless networks," *ACM Wireless Networks*, Vol.8, No.5, Sept. 2002.

[11] J. Wu, F. Dai, M. Gao, and I. Stojmoenovic, " On calculating power-aware connected dominating sets for efficient routing in ad hoc wireless networks," *Journal of Communications and Networks*, 4 (1), March 2002.

[12] Y. Xu, J. Heidemann, and D. Estrin, "Geography-informed energy conservation for ad hoc routing," *Mobicom 2001*.

[13] D.M. Blough, M. Leoncini, G. Resta, and P. Santi, " The k-NEIGH protocol for symmetric topology control in ad hoc networks," *MobiHoc 2003*.

[14] L.M. Feeney, "A QoS aware power save protocol for wireless ad hoc networks," *INFOCOM 2002*.

[15] R. Ramanathan and R. Rosales-hain, "Topology control of multihop wireless networks using transmit power adjustment," *INFOCOM 2000*.

[16] J. Gomez and A. Campbell, "Power-aware routing optimization for wireless ad hoc networks," *High Speed Networks Workshop (HSN)*, June 2001.

[17] J.-H. Ryu and D.H. Cho, "A new routing scheme concerning power-saving in mobile ad hoc networks," *ICC 2000*.

[18] A. Avudainayagam, W. Lou, and Y. Fang, "DEAR: A device and energy aware routing protocol for heterogeneous ad hoc networks," *Journal of Parallel and Distributed Computing*, Feb. 2003.

[19] V. Ramasubramanian, R. Chandra, and D. Mosse, "Providing a bidirectional abstraction for unidirectional ad hoc Networks," *INFOCOM 2003*.

[20] S. Nesargi and R. Prakash, "A tunneling approach to routing with unidirectional links in mobile ad-hoc networks," *ICCCN 2000*.

[21] http://www.opnet.com.

[22] J. Yoon, M. Liu, and B. Noble, "Sound Mobility Models", in Proc. of ACM MOBICOM'03, September 2003, San Diego, CA.

[23] http://www.proxim.com/learn/library/datasheet/11abgcombocard.pdf