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Raymond Yim, Neelesh Mehta, Andreas Molisch, Jinyun Zhang

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Index Terms— **Communication system routing, distributed algorithms, energy accumulation, radio networks**

I. INTRODUCTION

Traditional wireless relay networks reduce the total energy required to deliver a unicast message from a source to a destination by utilizing short hops [6]. The message propagates from the source to the destination through intermediate relay nodes along a pre-determined energy-efficient route. In these networks both relay nodes and the destination node discard a message if they cannot decode the received message successfully. This approach is sub-optimal, as many of the nodes make no use of the received versions of the transmitted signal [10].

Energy accumulative routing has been recently proposed to improve the energy efficiency of wireless relay networks [2, 4, 5, 7]. In energy accumulative routing, a node can *store* a received signal that is too weak for decoding, and combine it with another version of the same packet that arrives later. The accumulation-based techniques envisaged in all the above papers work on the idealized premise that every node stores each and every received copy of a packet that is transmitted from multiple nodes in the network until it can successfully decode it. After successfully decoding, the relay node can also transmit the message to propagate it through the network.

While current and next generation wireless systems do have mechanisms in place to implement energy accumulation, doing so at each and every node is challenging. In a typical network, the source will send multiple messages one after the other. The relays will then have to store multiple "soft" copies of not one but many messages that are transmitted by all the nodes that have already decoded these messages and the source. To make matters worse, relay nodes can act as relays for different sources, so that their storage effort is proportional to the total number of distinct messages "in transit" in the network. Since the nodes acting as relays do not directly benefit from transmitting a message from a source to a destination, it is difficult to justify their having to dedicate the significantly greater resources required by energy accumulative routing. Finally, finding the optimal energy-accumulative route in a given wireless network consisting of many relay nodes and jointly determining the transmit power levels of the nodes in the route is extremely difficult: [4] showed that for unicast transmission, finding the Minimum Energy Accumulative Route (MEAR) is an NP-Complete problem. Thus, no *scalable* optimum mechanism exists.

In this paper, we focus on an intermediate case we call *destination energy accumulation (DEA)*, which fills the gap between the two extremes considered in the literature, namely (i) a traditional network, which requires simple decode-and-forward relays but does not exploit the benefits of energy accumulation, and (ii) a complete energy-accumulation network, which requires highly complex decode-and-forward relays that can accumulate energy to the greatest possible extent. In our setup, only the destination node uses energy accumulation to decode the message, while the intermediate relays do not. Energy accumulation at the destination is justifiable because (i) in many sensor network applications, the message sink (destination node) can have the higher complexity required to so process the received signals, (ii) the additional effort of accumulation occurs at the node that benefits from it, and (iii) the number of messages that need to be accumulated and stored is limited. Furthermore, as we shall see, energy accumulation at the destination reduces energy consumption throughout the network. Another critical advantage of only considering energy accumulation at the destination is that it significantly simplifies the route setup protocol and makes a practical implementation feasible.

In this paper, we propose and develop the *Progressive Accumulative Routing* (PAR) algorithm that determines the energy-efficient routes and sets the node transmit powers in a distributed and progressive manner. As a distributed algorithm, PAR establishes energy-efficient energy-accumulative routes based on only the local channel knowledge available at each relay node. The progressive nature of the algorithm enables it to incrementally add new relays to an established accumulative route and realize additional energy savings. When a relay forwards a packet, neighboring nodes determine if they satisfy certain criteria and then deliver the necessary information

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to the relay to help it establish a better route. As we will show in this paper, DEA using the PAR algorithm improves the energy-efficiency compared to traditional non-accumulative networks and is only slightly worse than the much more complicated complete energy accumulation (i.e., accumulation at each node). The results developed in this paper also lay the foundation for a more elaborate routing algorithm that allows the use of more powerful relays – should they be available – as intermediate destinations [12].

While there are a number of routing algorithms for energy-accumulation networks, none of them is suitable for the situation we consider. The heuristic algorithm suggested in [4] is intended for full energy accumulation. Another drawback is that it requires fully centralized information, i.e., every node needs to be aware of the states of the the links between all the nodes in the network. The methods developed in [2, 7] are designed for broadcast and not unicast. While [8] considered energy-accumulative routing for multicast, of which unicast can be considered a special case, the objective of maximizing the network lifetime is different from ours. The PAR algorithm we develop in Section IV is thus the first distributed algorithm suitable for unicast with DEA.

The remainder of this paper is organized as follows. In Section II, we present the network model used in this work. In Section III, we lay the theoretical foundation of the PAR algorithm. In Section IV, we describe the PAR algorithm in detail. We present simulation results in Section V followed by our conclusions in Section VI.

II. NETWORK MODEL

We consider the problem of unicast traffic in a wireless network that consists of a source node, s, a destination node, t, and intermediate decode-and-forward relay nodes. All nodes use a single omnidirectional antenna for transmission and reception. The network is quasi-static, in which occasional link updates reflect the possible changes of the channel state of the network. Let V be the set of nodes in a network. For $u, v \in V$, let h_{uv} be the channel (power) gain between the nodes u and v. Each node, $u \in V$, only knows the power of the links to its neighbours, $v \in V$ ($v \neq u$). The phase information of the channel need not be known. A node does not know the channel gain of any other link in the network.

A node can forward a message only after having reliably decoded that message. As discussed in the Introduction, we assume that the destination accumulates energy, while the intermediate relays do not. The destination receives multiple "soft" copies of the same packet (at different times) from multiple nodes and stores all of them. The packet can be successfully decoded at the destination once the total energy accumulated from the multiple received copies exceeds the threshold $\bar{\gamma}$. This is akin to the Chase combining technique used in third generation cellular receivers [1, 3].[1]

If the destination receives one copy of the message from each of the nodes $u_1, u_2, \cdots, u_n$, then it can decode the message successfully if $\sum_{k=1}^{n} p_k h_{u_k t} \geq \bar{\gamma}$, where p_k is the transmit power of node u_k and $\bar{\gamma}$ is a threshold that depends on the modulation and coding used for transmission. An intermediate node v can successfully decode the message transmitted by node u with power p if and only if $p h_{uv} \geq \bar{\gamma}$; otherwise, it discards the packet. Without loss of generality, the packet duration is normalized to unity; we therefore interchangeably use energy and power.

III. FUNDAMENTALS OF PAR

In this section, we lay the mathematical foundation for the development of the PAR algorithm. We first derive the general conditions for power saving when a single relay is introduced between the source and the destination, and when a second relay is introduced in an energy-accumulative route that contains one relay. We shall see that very limited information is often needed to determine the optimal relay. We then extend the result to a general energy-accumulative route that contains an arbitrary amount of relays. We shall again see that additional energy savings can be achieved using the local information at the relays, and with limited additional information.

A. Adding the First Relay Between Source and Destination

Lemma 1: An accumulative route from s to t through r can reduce the total power consumption if and only if there exists a node, r, such that

$$h_{st} < \min\{h_{sr}, h_{rt}\}. \tag{1}$$

The maximum total power saving, $P_s^{\text{sav}}(r)$, by having r as a relay is given by

$$P_s^{\text{sav}}(r) = \left(1 - \frac{h_{st}}{h_{sr}}\right)\left(1 - \frac{h_{st}}{h_{rt}}\right)\frac{\bar{\gamma}}{h_{st}}, \tag{2}$$

and is achieved when s and r set their transmission powers P_s and P_r, respectively, at

$$P_s = \frac{1}{h_{sr}}\bar{\gamma}, \quad \text{and} \quad P_r = \frac{1}{h_{rt}}\left(1 - \frac{h_{st}}{h_{sr}}\right)\bar{\gamma}. \tag{3}$$

■

For the sake of brevity, we omit all proofs from this paper. Please refer to [11] for details.

Lemma 1 shows that only nodes which satisfy (1) are eligible candidates for reducing energy consumption. Note that for the source to determine which node is the best relay, it only needs to know h_{rt} in addition to the local information it already has. And if s is sending a packet directly to t, all the eligible relays can decode the packet because $h_{sr} > h_{st}$.

The condition in (1) is very closely related to the relative neighborhood graph (RNG) [9], which was defined for the special case in which the channel gain only depends on the path loss. Specifically, let $d(u, v)$ be the Euclidean distance between nodes u and v. Then, the graph $(V, RNG(V))$, consisting of the vertices V and the edges $RNG(V)$, is called the *relative neighborhood graph* of V if, for all edges $(u, v) \in RNG(V)$, and for any node $w \in V$ ($w \neq u$),

$$d(u, v) \leq \max\{d(u, w), d(v, w)\}. \tag{4}$$

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[1] A repetition coding based justification for the wideband regime was provided by [7], and Maximum Ratio Combining was used by [2] to also justify this.

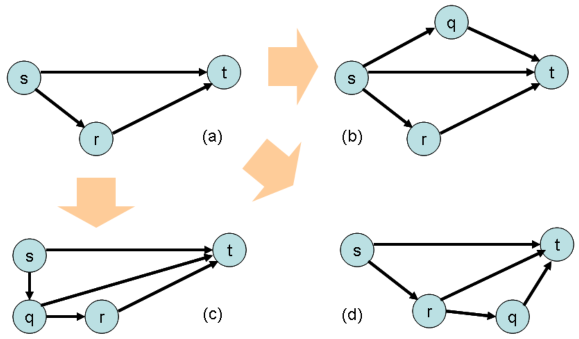

Fig. 1. There are three ways to introduce a second relay to the one relay configuration shown in (a): (b) Second relay is added in parallel to the established DEA route, (c) Second relay is added between the source and the first relay, (d) Second relay added between the first relay and the destination.

B. Adding the Second Relay

Let r denote the first relay already present in the network. As shown in Fig. 1, three possibilities exist for adding a second relay to a DEA route that consists of three links: s–r, r–t, and s–t. The following Lemma shows that one of the possibilities is always sub-optimal and need not be considered.

Lemma 2: If the relay r is the optimal single relay for cooperating in the transmission from s to t, adding an additional node, q, in parallel between s and t (as in Fig. 1b) cannot reduce the total transmission power in DEA. ■

Lemma 2 simplifies the search for the second relay, as we only need to consider adding a new node in between two adjacent relays in the established DEA route, as shown in Fig. 1c and Fig. 1d.

C. When Multiple Relays are Present

In the previous subsection, we saw that two relays in parallel cannot reduce the total power consumption over an optimal single relay DEA route. This result generalizes to the case when more than two relays are present in the DEA route. Henceforth, we only need to consider the case where new nodes are added in between two adjacent relays in the established DEA route in a fashion similar to that described in Fig. 1c and Fig. 1d. We refer to this as *serial DEA route*.

To consider adding a node, w, in a serial DEA route that already contains multiple relays, we first define the following terminology. If u and v are two relays in a serial DEA route, and u successfully decodes the packet before the relay v, then we say that u is *before* v and v is *after* u. We say that v is *immediately after* or *next to* u if v is after u and there is no relay that is after u and before v. The relay immediately after u in the serial DEA route is denoted by $N(u)$. A relay u is called the *last relay* in the serial DEA route if $N(u) = t$.

The *relay set*, R, is the set of all relays, excluding the destination, that are in the serial DEA route. The *backward relay set*, $B(u)$, is the ordered set of relays *before* u in the route. $A(u) = \sum_{r \in B(u)} \frac{h_{rt}}{h_{rN(r)}}$ denotes the fraction of the total energy, which is required to successfully decode a packet at the destination, that accumulates at the destination due to transmissions from the relays in the set $B(u)$.

Theorem 1: Let u be a relay in the serial DEA route, with $v = N(u)$ being the relay immediately after it. If u is not the last relay, l, in the route, then adding the node w as a relay immediately after u reduces the total power consumption if w satisfies the following two sufficient conditions:

$$h_{uw} > h_{uv} \quad \text{and} \quad h_{wv}\left(\frac{1}{h_{uv}} - \frac{1}{h_{uw}}\right) > \frac{h_{lt} - h_{wt}}{h_{lt} - h_{ut}}. \tag{5}$$

A maximum total power saving of

$$P_u^{\text{sav}}(w) = \frac{1}{h_{lt}}\left[(h_{lt} - h_{ut})\left(\frac{1}{h_{uv}} - \frac{1}{h_{uw}}\right) + \frac{h_{wt} - h_{lt}}{h_{wv}}\right]\bar{\gamma} \tag{6}$$

is achieved when the transmit powers of u and l are changed to

$$\begin{aligned} P_u &= \frac{\bar{\gamma}}{h_{uw}}, \text{ and} \\ P_l &= \frac{1}{h_{lt}}\left(1 - A(l) + \frac{h_{ut}}{h_{uv}} - \frac{h_{ut}}{h_{uw}} - \frac{h_{wt}}{h_{wv}}\right)\bar{\gamma}. \end{aligned} \tag{7}$$

The transmit power of the new relay, w, is $P_w = \bar{\gamma}/h_{wv}$. The transmit powers of all the other relays in the route are unchanged. ■

To achieve the power savings, the condition in (5) requires that every relay in the serial DEA route know h_{lt}, which is not conducive to a distributed implementation. The following Corollary, stated without proof, provides a sufficient condition that guarantees power savings without the need for every relay knowing h_{lt}.

Corollary 1: When u is not the last relay in a serial DEA route, adding a node w immediately after u results in power savings if

$$h_{wt} > h_{ut} \quad \text{and} \quad \frac{1}{h_{uw}} + \frac{1}{h_{wv}} < \frac{1}{h_{uv}}. \tag{8}$$

■

Theorem 2: When u is the last relay in a serial DEA route, adding a node w immediately after u can reduce power consumption if w satisfies the two conditions:

$$h_{wt} > h_{ut} \quad \text{and} \quad \frac{h_{ut}}{h_{uw}} < 1 - A(u). \tag{9}$$

A total power saving of

$$P_u^{\text{sav}}(w) = \left(\frac{1}{h_{ut}} - \frac{1}{h_{wt}}\right)\left(1 - A(u) - \frac{h_{ut}}{h_{uw}}\right)\bar{\gamma} \tag{10}$$

is achieved when the transmit power of u is changed to $P_u = \bar{\gamma}/h_{uw}$, and the transmit power of the new node w is

$$P_w = \frac{1}{h_{wt}}\left(1 - A(u) - \frac{h_{ut}}{h_{uw}}\right)\bar{\gamma}. \tag{11}$$

The transmit powers of all the other relays are unchanged. ■

Both Theorem 2 and Corollary 1 show that all potential relays (the nodes that lead to power savings if made relays) can already successfully decode the transmissions from the relay that they will be immediately after. As a result, local CSI and minimal feedback from the potential relays can be used to progressively increment the serial DEA route to save total power.

IV. THE PAR ALGORITHM

The PAR algorithm is a distributed algorithm for progressively determining relays to enable DEA routing. It requires the use of two types of packets: a *data* packet that contains the data sent from the source, s, to the destination, t, and a *ready-to-cooperate (RTC)* packet for feedback of the limited additional information required for modifying the route.

Initially, we assume that a basic route is established between the source and the destination.[2] At any time, the source transmits data to the destination through an already established serial DEA route. It transmits a new packet to its next relay, $N(s)$, with power $\bar{\gamma}/h_{sN(s)}$. Neighboring nodes that overhear the transmission from a currently transmitting relay in an established serial DEA route check – using only the local information available to them and the information in the data packet – whether their participation can lead to further power savings. If so, they feedback an RTC packet to the corresponding relay.

The structure of the data and RTC packets is shown in Fig. 2. To explain each of the fields in the packets, we assume that the data packet is transmitted by relay u, and the RTC packet is generated by node w and sent to u. The node immediately after u is v. The fields `MSrc`, `MDest`, `RSrc` and `RDest` have the same following meaning in both data and RTC packets:

- `MSrc`: The source, s, where data originates.
- `MDest`: The destination, t, of data.
- `RSrc`: The relay, u, that transmits the packet.
- `RDest`: The relay, v, immediately after u.

The fields that are specific to the data packet are:

- `GainD`: The channel gain, h_{ut}, from the current relay, u, to the destination, t.
- `GainR`: The channel gain, h_{uv}, from u to the relay, v, immediately after u.
- `FracDelivered`: The fraction of total energy, which is required to successfully decode a message at the destination, that has been accumulated at the destination before u transmits: $A(u) = \frac{h_{st}}{h_{sq}} + \frac{h_{qt}}{h_{qu}}$.

The fields that are specific to the RTC packet are:

- `GainD`: The channel gain, h_{wt}, from the node generating the RTC packet to the destination, t.
- `GainR`: The channel gain, h_{wv}, from the node generating the RTC packet to the relay, v, immediately after u.
- `RelayID`: The identity, w, of the node transmitting the RTC packet.

The pseudocode of the PAR algorithm is shown in Fig. 3. When a relay u (that is not the source) successfully decodes the header of the data packet `p`, it acts upon it only if `p.RDest` $= u$. It then knows that the final destination is `p.MDest`, and the total power that will accumulate at the destination after `p` is transmitted by it is `p.FracDelivered` + `p.GainD`/`p.GainR`. If u is not the last relay, it relays the message to its next relay with power $\bar{\gamma}/h_{uN(u)}$. If it is the last relay, it transmits the packet to the destination with power $(1 - A(u))\bar{\gamma}/h_{ut}$.

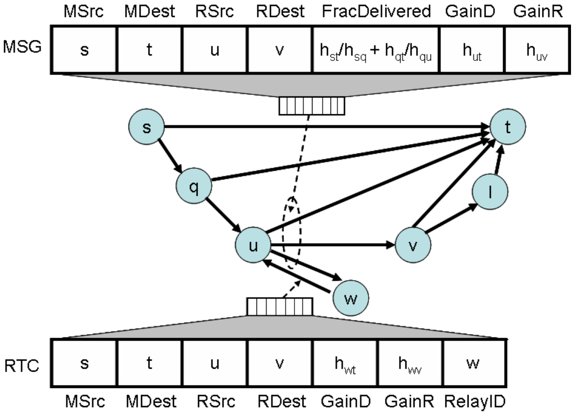

Fig. 2. Overview of the PAR protocol. The top of the figure shows the overhead sent in the data packet transmitted by relay u. The bottom of the figure shows the *Ready-to-cooperate (RTC)* message from a potential relay w.

The relay u updates the route after a sufficient time, `minTime`, has elapsed since it last updated the route. `minTime` depends on the multiple access protocol, and is used to ensure that a relay has sufficient time to receive RTC feedback packets before it decides on an additional relay. It updates the next relay to be the node (denoted by `bestCandidate`) that leads to maximum power savings. The RTC packets u receives enable it to find `bestCandidate`. When u receives an RTC packet from node w, the fields of the packet enable u to compute the power savings if w is made its next relay as follows:[3]

If u is not the last relay,

$$\tilde{P}_u^{\text{sav}}(w) = \left(\frac{1}{h_{uv}} - \frac{1}{h_{uw}} - \frac{1}{h_{wv}}\right)\bar{\gamma}, \tag{12}$$

If u is the last relay,

$$\tilde{P}_u^{\text{sav}}(w) = \left(\frac{1}{h_{ut}} - \frac{1}{h_{wt}}\right)\left(1 - A(u) - \frac{h_{ut}}{h_{uw}}\right)\bar{\gamma}, \tag{13}$$

where v is the relay immediately after u: $v = N(u)$. If $\tilde{P}_u^{\text{sav}}(w)$ exceeds the power savings achievable by the current best candidate, we update `bestCandidate` to be w.

When a node w overhears a data packet, `p`, from the relay u, the fields of the data packet enable it to check, using (8) or (9), whether its becoming a relay can reduce total power consumed by the route. If so, it stores $N(w) =$ `p.RDest` in memory, and generates and sends an RTC packet to u when possible (according to the multiple access protocol in operation). The pseudo code for a node is given in bottom portion of Fig. 3.[4]

It must be noted that while the PAR algorithm does guarantee power savings in every progressive step, it may be not be optimal when many relays are present. For example, let the source, s, be located at $(-5, 0)$ and the destination, t, be at $(5, 0)$. Three other nodes, a, b and c, are located at $(0, -3)$, $(-1, 2.5)$, and $(1, 2.5)$, respectively. Say the channel gain between any two nodes u and v is determined by the path loss as

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[2] Traditional routing algorithms can be used to discover a route between s and t in large networks. This extension is discussed in [12].

[3] Notice that $\tilde{P}_u^{\text{sav}}(w)$ in (12) is obtained from $P_u^{\text{sav}}(w)$, defined in (6), by assuming that $h_{lt} \gg h_{ut}$ and $h_{lt} \gg h_{wt}$. This is justifiable because h_{lt} is not available at u and the last relay is often much closer to the destination than to the other relays.

[4] We omit the multiple access aspects of the feedback mechanism in this paper. This issue is discussed in [12].

```
Relays execute the following when they receive a packet:
1. When a packet with p.type = data and
         p.RDest = $u$ is received:
   Construct data Packet q
   assign $A(u) \leftarrow$ p.FracDelivered
   assign q $\leftarrow \Big($p.MSrc, p.MDest, $u, N(u),$
                 $A(u) + \frac{\text{p.GainD}}{\text{p.GainR}}, h_{ut}, h_{uN(u)}\Big)$
   if $u$ is not the last node
      Transmit packet q using power $\bar{\gamma}/h_{uN(u)}$
   else
      Transmit packet q using power $(1 - A(u))\bar{\gamma}/h_{ut}$
   end if
2. When a packet with p.type = RTC, p.RSrc = $u$,
         and p.RDest = $N(u)$ is received:
   $thisSav = \tilde{P}_u^{sav}$(p.RelayID)
   if $thisSav > powSav$
      bestCandidate = p.RelayID
      $powSav = thisSav$
   end if
3. After minTime has elapsed since last update
         and bestCandidate $\neq$ null:
   assign $N(u) \leftarrow$ bestCandidate
   assign bestCandidate $\leftarrow$ null
   assign $powSav \leftarrow 0$
Other nodes execute the following when they receive a
packet:
Quit if p.type $\neq$ data
assign $u \leftarrow$ p.RSrc
assign $v \leftarrow$ p.RDest
Quit if $h_{wt} \leq$ p.GainD
Quit if $v \neq t$ and $\frac{1}{h_{uw}} + \frac{1}{h_{wv}} \geq \frac{1}{\text{p.GainR}}$
Quit if $v = t$ and p.GainD $\geq (1 -$ p.FracDelivered$)h_{uw}$
assign $N(w) \leftarrow$ p.RDest, and store it in memory
Construct RTC packet q
assign q $\leftarrow$
      (p.MSrc, p.MDest, p.RSrc, p.RDest, $w, h_{wt}, h_{wv}$)
Transmit q using power $\bar{\gamma}/h_{uw}$ when possible
```

Fig. 3. Overview of the PAR algorithm.

$h_{uv} = 1/d(u,v)^\alpha$, where the path-loss exponent $\alpha = 4$. We can show that the PAR algorithm leads to a serial DEA route $s \to b \to a \to c \to t$. However, the optimal serial DEA route is actually $s \to b \to c \to t$, which consumes 3 dB less power than the route found by PAR.

V. SIMULATIONS

We consider a wireless network with 100 nodes that are uniformly distributed in a grid of size 20 × 20 units. In Cartesian coordinates, the source is located at $(5, 10)$, and the destination is at $(15, 10)$. The SNR threshold, $\bar{\gamma}$, is set to unity. The channel gain h_{uv} between any two nodes u and v that are $d(u,v)$ apart is given by $h_{uv} = 1/d(u,v)^\alpha$. At every progressive step, we assume that the relays have sufficient time to determine, using the RTC packets of PAR, the best candidate to add to the DEA route after them.

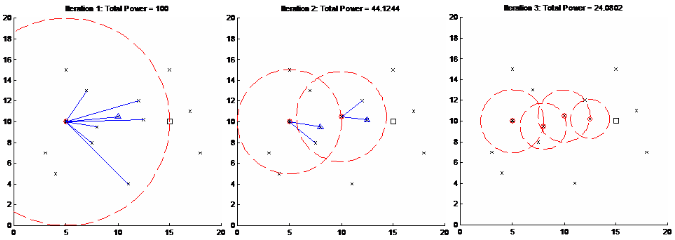

Fig. 4. Demonstration of the PAR algorithm. Crosses (×) represent the nodes in the network. A solid circle signifies that the node is active in the accumulative route. The larger dashed circle represents the range up to which the node can be heard given the transmission power set by the PAR algorithm. RTC packets arriving at a relay are shown by straight lines. The best candidate node determined by PAR that leads to the maximum power savings is shown by △.

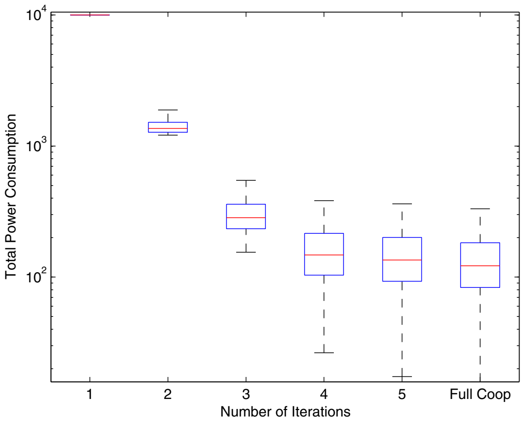

Fig. 5. Distribution of total power consumption for sending a packet to the destination as a function of the number of iterations of the PAR algorithm. The top, middle, and bottom lines of the box represent 75 percentile, median (50 percentile), and 25 percentile, respectively. The dashed-lines (- -) extending from each end of the boxes show the extent of the rest of data. The distribution of the total power consumed if all relays (not just the destination) accumulate energy is shown in the last column ('Full coop').

Figure 4 shows how PAR works, with 13 nodes and $\alpha = 2$. The range circles show that far transmissions can be successfully decoded on their own (without energy accumulation). Also shown is the RTC feedback from potential relays. After 3 iterations, the number of relays increases from 0 to 3, and the total power decreases to just 24.0% of the original value. It can be seen that the transmission from the last relay (- - circle line) does not include the destination because the destination has accumulated energy from transmissions of relays before the last relay.

We now study the statistics of the total power consumed by the routes established by PAR over 2000 random placements of 100 nodes and $\alpha = 4$. Figure 5 shows the probability distribution of the total transmit power as a function of the number of iterations of the PAR algorithm. The PAR algorithm considerably decreases the total power consumption after only 5 iterations. In the first five iterations, the median total power consumption decreases from 100% to 13.6% to 2.84% to 1.47% to 1.35%. The last column in the figure also shows the probability distribution of the total power consumed when *all* relays accumulate energy using the same route. It can be seen that DEA using PAR is within 0.44 dB of complete energy accumulation.

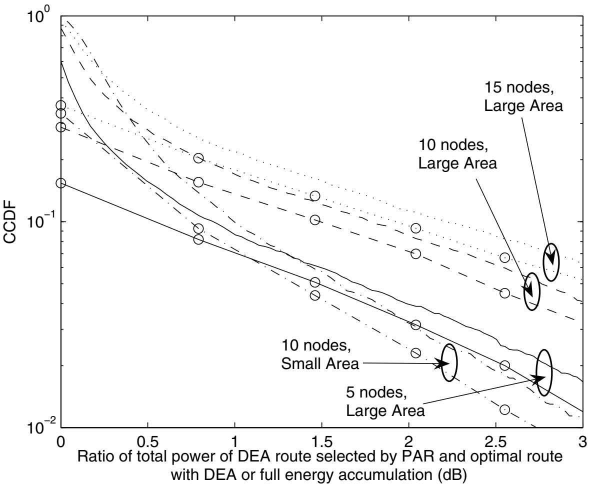

Fig. 6. The CCDF of the ratio of the total power usage of PAR algorithm and MEAR with full energy accumulation or optimal DEA. Large and small areas refer to grid sizes of 10×20 and 10×4, respectively. The lines without circles shows the comparison to MEAR with full energy accumulation, while the lines with circles shows the comparison to the optimal DEA route.

While Fig. 5 allowed for complete energy accumulation, it did not optimize its route. This is dealt with in detail in Fig. 6, which compares PAR with (i) MEAR that uses full energy accumulation and route optimization, and (ii) optimal DEA that uses global information to set up the route. We generate results for 5, 10 and 15 nodes in the network, each with 5000 random placements. The networks operate over a geographical grid of size 10×20 units with bounding corners at $(5, 0)$ and $(15, 20)$.[5] The other simulation parameters are the same as before. The figure shows the CCDF of the ratios of the total power usage of the PAR algorithm and that of the other two benchmark cases. For 5, 10 and 15 nodes, with a probability of 50%, the PAR routes are less than 0.034, 0.167 and 0.269 dB away, respectively, from MEAR. Furthermore, PAR is less than 0.5 dB away from MEAR with a probability of 83%, 73% and 66%, respectively. Similarly, PAR is less than 0.5 dB away from optimal DEA with a probability of 90%, 81%, and 75%, respectively. In all cases, PAR performs as well as the optimal DEA with a probability of 60%. Finally, when we consider a smaller area of size 10×4 units (with bounding corners at $(5, 8)$ and $(15, 12)$), but with the same 10 nodes, PAR is less than 0.25 dB away from MEAR with a probability of 50%, and is less than 0.5 dB away from MEAR with a probability of 77%.

Not shown in the figure is a comparison of the total powers consumed by PAR and conventional relaying (no DEA) as a function of the node density. For this, 5, 10, and 15 nodes were randomly placed over an area of size 10×20 units. In all three cases, PAR reduces the total power consumption by more than 0.2 dB in over 50% of the scenarios, and by more than 0.6 dB in over 10% of the scenarios for $\alpha = 3$. These numbers increase to 0.7 dB and 1.2 dB, respectively, for $\alpha = 2$. It must be noted, however, that the benefits from DEA decrease as α increases, or as the node density increases, since the transmission power of each relay decreases much faster than the number of relays from which the destination can accumulate energy.

VI. CONCLUSIONS

We investigated the performance of unicast sensor networks with DEA, i.e., where the destination node uses energy accumulation, while the relay nodes employ decode-and-forward. We showed that such networks have comparable energy efficiency as those in which energy accumulation occurs at every node, while greatly reducing the complexity and energy overhead of the relay nodes. Furthermore, DEA is somewhat more energy-efficient than traditional multi-hop networks that do not accumulate energy. The relative merits of DEA compared to full energy accumulation or traditional routing strongly depend on the number of nodes, the networks configuration, as well as the pathloss exponent. We developed an algorithm called PAR that performs the route discovery in a distributed manner. It requires only local information (i.e., information about the channel gains to the neighboring nodes) and very limited feedback from nodes that successively decode the message from an established serial DEA route. The finding of the route thus has a low complexity – in contrast to route discovery in full-accumulation networks, which is NP-hard. This allows our algorithm to attain a low route setup latency, as a less power efficient link is established even from the beginning, and link quality improves only when it is used frequently. Our algorithm can thus be used for reducing energy consumption in practical sensor networks with low mobility and low node complexity.

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[5] Considering more nodes is computationally cumbersome given the NP-complete nature of the MEAR problem [4].