Residual-Energy-Activated Cooperative Transmission (REACT) to Avoid the Energy Hole

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***Abstract*—In a multi-hop wireless sensor network (WSN) with a constant node density, the nodes that are one hop away from the Sink die first and cause an "energy hole," because they must forward the traffic from the rest of the network. When this hole forms, a large amount of "excess" energy is trapped in the other nodes. In this paper, we propose that some of those other nodes use some of the excess energy to do cooperative transmission (CT) to hop directly to the Sink, thereby relieving the nodes near the sink of some of their burden and balancing the energy consumption across the network. The REACT protocol triggers CT range extension when the next-hop node along a primary route has a lower residual energy than the current node. The paper considers several criteria for selecting the cooperators, and compares our proposed scheme to the AODV and CMAX multi-hop protocols through simulation.**

I. Introduction

In Wireless Sensor Networks (WSNs), the data collected from the sensors is usually gathered in a single base (Sink), which is considered to have no energy constraint and unlimited resources. In a multi-hop environment, this many-to-one wireless network is known to pose a so-called "energy hole" problem, which can be described as the situation when the nodes around the Sink consume relatively more energy and die early causing the rest of the network to become disconnected from the Sink. To cope with this problem, the non-uniform distribution strategy has been suggested, which is basically placing more radios in the area near the Sink [1] [2]. This can mitigate the energy hole problem, however, the additional nodes raise the cost. Using mobile nodes to mitigate uneven energy consumption is introduced in [3] and [4]. By changing the location of the Sink or relays, this mobile node strategy can balance the energy consumption of the nodes. However, this can be applied only to a limited situation because the nodes have to be mobile. Also, mobile nodes may be hard to operate in certain environments such as under the bridge, on the water, and in an unpaved area.

In this paper, we avoid the energy hole by using cooperative transmission (CT) [5] with the range extension strategy. Using CT to extend the lifetime of the network has been proposed in several papers [6] [7], which focus on using cooperative diversity gain to reduce the transmit power of the node. However, with this transmit power saving strategy of CT, it is not hard to see that the nodes one hop away from the Sink still have to receive and take care of all the packets passing through them, thereby creating the energy hole. Also, as discussed in [8], because of the circuit energy consumption, using transmit power saving strategy of CT may not be energy-efficient in terms of the total energy consumption when the distance between two communicating nodes is not large enough. Therefore, using CT to save the transmit power may not always guarantee the lifetime extension of the network.

When the energy hole forms, a large amount of energy is trapped in the nodes outside of the hole. We propose to apply the range extension strategy of CT to reduce the loads of the highly-burdened nodes by exploiting the energy of less burdened nodes. We develop this idea into a distributed protocol which we call "Residual-Energy-Activated Cooperative Transmission (REACT)." Through REACT, the unused energy of the network can be successfully utilized and this leads to as much as a factor of 8 network lifetime extension. It will be shown through simulations that the extension of the network lifetime from REACT increases as the energy hole problem becomes more severe, i.e. when the nodes that are one hop away from the Sink become a smaller fraction of the total number of nodes in the network.

II. The Description of the Algorithm

In this section, we explain and develop a CT method that utilizes the range extension strategy of CT. The cross-layer framework that can realize the range extension is introduced in detail in [9]. Now, with the help of the range extension, instead of using a conventional non-CT link, a virtual Multiple-Input Single-Output(MISO) link longer in range than non-CT link can be formed [9] and the nodes more than one-hop away from the Sink can directly communicate with the Sink. This is illustrated by the dashed line in Fig. 1. Note that the key point of our approach is to jump over the highly-burdened nodes using the energies of the others, which are going to be unused and wasted anyway if the highly-burdened node dies early. Doing CT every time may cause the excessive energy usage for the nodes that participate in CT, which leads those nodes to be highly-burdened and results in the nodes far away from the Sink dying early. Therefore, the mechanism that regulates the usage of CT, which will be introduced in this paper, is essential. We assume that the nodes other than the Sink are homogeneous, have non-rechargeable batteries, and are able to adjust their transmit power.

A. Terms and Definitions

Most cooperative routing protocols [9] [10] first form a *primary route* using a conventional non-CT routing scheme. A node in a primary route initiates the cooperation and selects the nodes to cooperate. We call this node a *leader* node. The leader

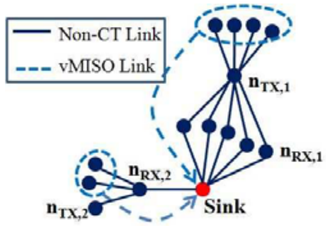


Fig. 1. An illustration of using CT for the range extension.

node should send its data packet to its cooperating neighbors and this is called the *local transmission*. The actual cooperative transmission is done after the local transmission, and we express this as "cooperators (or nodes) do CT." Depending on situations (not sufficient number of cooperators, neighbors are busy, etc.), CT may not be possible. In this case, the leader may just forward the packet to the next hop node in the primary route. We express this as "the node does non-CT." The network is considered *dead* when one of the nodes in the network dies, which is widely used [11] [12]. We note that when the energy is well balanced, the majority of the nodes die soon after the first death. We measure the *lifetime* by calculating the total number of packets transmitted till the network is dead [12], which will be called the *lifetime throughput* [13].

The distance between the node n_i and the Sink is defined as $d_s(n_i)$. The residual energy of the node n_i will be denoted as $E_{\text{re}}(n_i)$. We define the set of nodes containing all cooperators as S_{CT} and the total number of cooperators as N_c ($|S_{\text{CT}}| = N_c$). We denote the leader node as n_{L} and the i-th cooperator as $n_{\text{C},i}$ ($1 \le i \le N_c$). We denote the transmitting node in a non-CT link as n_{TX}, and the receiving node as n_{RX}.

Each cooperator transmits in a channel that is orthogonal to the others. The cooperative diversity gain is a monotonically increasing function of N_c, and will be denoted as $G(N_c)$, and the maximum number of the orthogonal diversity channels will be denoted as N_d. Note that N_c should satisfy $2 \le N_c \le N_d$. The maximum transmission range of a single node will be denoted as $d_{\text{tx}}^{\max}$. We define C_i as the area of a circle with its center at the location of the Sink and with a radius of $i \times d_{\text{tx}}^{\max}$, and $A_i = C_i - C_{i-1}$ where $i \ge 1$ and $C_0 = 0$. Then, the nodes in A_1 will be the ones that are one-hop away from the Sink.

Now, we provide the equations related to the range extension strategy of CT and define several terms required to explain our algorithm. Consider the case when a node with a single antenna is transmitting (non-CT) with power P_{tx} over a distance d_{link}. Then the received power at the destination, P_{rx}, can be expressed as $k \cdot P_{\text{tx}}/d_{\text{link}}^{\alpha}$ where α is the path loss exponent and k is a constant of proportionality [14]. Conversely, the transmit power of $P_{\text{tx}} = P_{\text{rx}} \cdot d_{\text{link}}^{\alpha}/k$ is required to guarantee a required received power of P_{rx}. Next, suppose that the single antenna transmitter is joined by $N_c - 1$ nearby radios to form a cooperating cluster of N_c nodes, transmitting in N_c orthogonal channels and each with power P_{tx}. The purpose of doing CT without reducing the transmit power is to communicate with the node which is farther than d_{link}. When N_c cooperators are relatively close to each other (compared to the destination far away from the nodes) so that the distances from each of these nodes to the destination, d_{ct}, are almost same, then the range extension factor, β_{ext}, defined as $d_{\text{ct}}/d_{\text{link}}$, equals $(N_c \cdot 10^{G(N_c)/10})^{1/\alpha}$ [9]. Table I gives some examples of $G(N_c)$ and β_{ext} for BPSK modulation at a bit error rate (BER) of 10^{-3} [15]. For example, if only two nodes cooperate, their range is 2.71 times longer than if only a single node transmits. Note that when the distance, d, between two communicating nodes is $d_{\text{link}} < d \le 2.71 d_{\text{link}}$ (Table I), only 2 cooperators are necessary, and more than 2 cooperators are unnecessary. Therefore, *the optimal number of cooperators* denoted as N_c^{opt} can be defined based on the distance between the nodes. $N_c^{\text{opt}} = 2$ for $d_{\text{link}} < d \le 2.71 d_{\text{link}}$, $N_c^{\text{opt}} = 3$ for $2.71 d_{\text{link}} < d \le 4.07 d_{\text{link}}$, and so on.

TABLE I
DIVERSITY GAIN AND RANGE EXTENSION (BPSK. BER = 10^{-3})

N_c	2	3	4	5	10
$G(N_c)$ (dB)	10	13.5	14	14.5	15.9
β_{ext} (α=3)	2.71	4.07	4.65	5.2	7.3

We want to use CT to "hop over" nodes in a route and reach the Sink directly, and this means that we want our extended range to be enough to reach the fixed destination. However, we desire not to use any more transmit power per node than necessary. Consider two cooperating nodes exactly $2d_{\text{link}}$ away from the Sink. When they use P_{tx}, it can be easily seen from Table I that they can surely reach the Sink, however, they are overusing the transmit power because with P_{tx}, they can reach the node $2.71 d_{\text{link}}$ away. Also, the assumption that cooperators are relatively close to each other has to be removed for the equation to be more practical. When N_c cooperators, each using the transmit power of $P_{\text{tx,min}} = P_{\text{rx}} \cdot d_{\text{req}}^{\alpha}/k$, do CT, they can reach the fixed Sink, which is $d_s(n_{\text{C},i})$ distance away from each cooperator $n_{\text{C},i}$, where

$$d_{\text{req}} = \left(10^{G(N_c)/10} \sum_{i=1}^{N_c} d_s(n_{\text{C},i})^{-\alpha} \right)^{-1/\alpha}. \quad (1)$$

We note that if $P_{\text{tx,min}}$ exceeds the maximum available transmit power per node, then CT cannot be done. In other words, if the following condition does not hold,

$$d_{\text{req}} \le d_{\text{tx}}^{\max}, \quad (2)$$

direct communication with the Sink using CT is impossible because of the transmission power limit, and when this condition is not satisfied, non-CT has to be performed.

B. The Trigger for Using CT

Suppose n_{TX} and n_{RX} (n_{RX} not being the Sink) are two communicating nodes in a primary route. n_{RX} should not only transmit its own data but also the data from n_{TX}. However, this does not necessarily imply that n_{RX} has a heavier burden then n_{TX}, because n_{TX} may have a lot of alternative paths to the Sink and also more burden than n_{RX} (the node $n_{\text{TX},1}$ in Fig.

1). In any case, we can conclude that the more burdened node will have less residual energy than the other as the time goes by. Therefore, in our algorithm, when n_{TX} has more residual energy than n_{RX}, n_{TX} tries to use CT for range extension to directly communicate to the Sink so that n_{RX} need not be used. To summarize, n_{TX} behaves as follows.

If $E_{\text{re}}(n_{\text{TX}}) > E_{\text{re}}(n_{\text{RX}})$: try CT for the range extension
If $E_{\text{re}}(n_{\text{TX}}) \leq E_{\text{re}}(n_{\text{RX}})$: do non-CT.

C. Selecting Cooperators for CT

When $E_{\text{re}}(n_{\text{TX}}) > E_{\text{re}}(n_{\text{RX}})$, n_{TX}, which is the leader node, tries to do CT and is in charge of selecting the cooperators. The leader has to choose the desired number of cooperators, N_c, and form S_{CT} in a way to protect the highly burdened node and extend the network lifetime. In order to maximize the minimum residual energy left after the data transmission, it is obvious that the leader must choose i) the nodes with high $E_{\text{re}}(n_i)$'s and ii) the nodes that give a low d_{req} (to reduce the transmit power). However, if we stick to this somewhat idealized selection method, the set S_{CT} may give small N_c, and this can lead to $d_{\text{req}} > d_{\text{tx}}^{\text{max}}$ (the violation of the condition in (2)) forcing the leader node to do non-CT, which can nullify our overall purpose of protecting n_{RX} using CT. Note that the idea and effectiveness of our approach comes from the fact that we can reduce the energy consumption of the highly-burdened node by jumping over that node using the energies of the others which are going to be unused anyway if the highly-burdened node dies early, rather than through optimizing the energy consumption. Therefore, we try to loosen idealized condition and find a reasonable way to select the cooperators.

The selection process mainly consists of two parts: i) selecting potential cooperators reasonably (the set of selected nodes will be denoted as S_{p}), and ii) among S_{p}, select desired number of cooperators, and check if the direct communication with the Sink using CT is possible.

In the first part of the selection process, the leader has to consider the nodes with high $E_{\text{re}}(n_i)$'s and the nodes that lead to low d_{req} for the cooperator selection. As can be seen from (1), low d_{req} can be achieved when the nodes with small $d_s(n_{\text{C},i})$ are selected. Therefore, it is evident that picking the nodes with high residual energy and short distance to the Sink is a good choice. Since "high" and "short" are also subjective matters, the average values, considering the leader and all its neighbors, are calculated and used as a guideline. That is, the leader node first calculates the average residual energy, $E_{\text{re}}^{\text{avg}}$, and the average distance to the Sink, d_s^{avg}. Then, the nodes, n_i's, that satisfy the following two conditions are identified as potential cooperators:

$$E_{\text{re}}(n_i) > max(E_{\text{re}}^{\text{avg}}, E_{\text{re}}(n_{\text{RX}})), \tag{3}$$

and

$$d_s(n_i) < d_s^{\text{avg}}, \tag{4}$$

where $max(\text{A, B})$ returns the largest of A and B. The reason why $E_{\text{re}}(n_{\text{RX}})$ is included in (3) is that there is no point in using the node having less residual energy than n_{RX} to protect n_{RX}. After this process, S_{p} is formed (the leader obviously cooperates and S_{p} is a subset of its neighbors not including the leader). Now, the second part of the selection process determines whether the direct communication to the Sink using CT is possible with the selected nodes in S_{p}. Note that, as mentioned earlier, the direct communication between cooperators and the Sink is possible if and only if the condition in (2) holds.

Before we explain the second part, let's consider the case when the direct communication to the Sink is impossible (i.e. the condition (2) does not hold). In this case, we may still be able to protect n_{RX} by loosening the conditions (3) and (4), thereby increasing the number of potential cooperators. Since the residual energy is a critical factor in network lifetime, (4) is removed, and the n_i's are selected using (3) only. A new S_{p} is formed and the second part of selection process (explained below) selects the nodes and checks the condition (2). If the condition (2) does not hold after the second selection process with the new S_{p}, the leader does not do CT. The importance of this loosening of the conditions is further explained in Section III.

The main objective of the second part of the selection is to choose the number of cooperators, N_c, appropriately. That is, we do not want N_c to be unnecessarily large, because it can increase the total energy consumption of doing CT especially when $E_{\text{RX}}^{\text{ckt}}$ is higher than other parts. In this selection process, cooperators and N_c have to be decided among the nodes in S_{p}, Since the leader node knows the distance between itself and the Sink, it can simply set $N_c = N_c^{\text{opt}}$. However, N_c^{opt} is not perfectly accurate because the range extension factor (such as 2.71, 4.07, Table I) obtained is based on the assumption that the cooperators are *relatively* close to each other. Nonetheless, it gives a good reference for how many cooperators are necessary. The leader first sets $N_c = N_c^{\text{opt}}$ and selects $N_c - 1$ nodes (including the leader results in N_c nodes) from S_{p} that have the highest residual energies. When nodes are determined (the leader is always included), d_{req} can be calculated using (1) and the condition (2) can be checked. If the condition (2) holds, the leader decides to do CT with the cooperation of N_c nodes. If the condition (2) does not hold, the leader sets $N_c = N_c + 1$ and repeats the process until N_c reaches $min(|S_{\text{p}}|, N_d)$. These steps are not necessary when $|S_{\text{p}}|$ happens to be less than $N_c^{\text{opt}} - 1$, and in this case, the leader can simply calculate d_{req} considering itself and all the nodes in S_{p} and check the condition (2). The combined selection process (including the first and the second parts) is summarized in Section II-D.

Note that if the leader node already has the required information of the neighbors such as $d_s(n_i)$ and $E_{\text{re}}(n_i)$, the procedures that we have introduced in this subsection and Section II-B can be done without any additional transaction with neighbors. This required information can be achieved by using a periodic message (HELLO) which is widely used in non-CT and CT routing protocols [16] [12] [9] [10].

Gathering the cooperators and doing CT can be done by using the cross-layer framework in [9]. However, this is not the only choice, and our algorithm can be built on top of any existing cross-layer framework designed to use cooperative transmission.

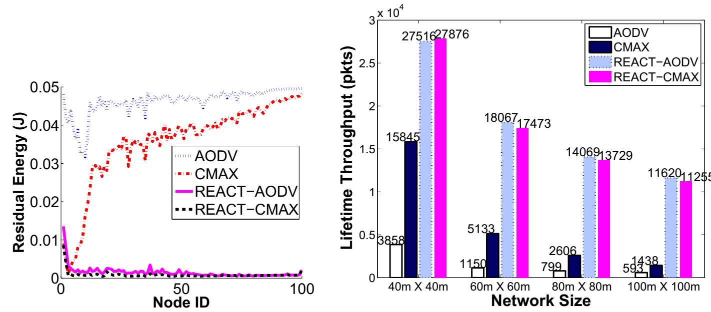
D. Summary of the REACT Protocol

When a source node needs to transmit the data to the Sink, it first establishes a primary route (or uses a pre-existing route). Then, along the primary route, when n_{TX} needs to transmit/relay the packet, it decides whether to do CT or not using the following procedure.

- **Step 0.** Set the variable 'num_trial' to 1. Also, $COND_A$ = (3) & (4), $COND_B$ = (3). Also, using its distance to the Sink, $d_s(n_{\text{TX}})$, obtain N_c^{opt}.
- **Step 1.** n_{TX}, the leader, checks the residual energy. If $E_{\text{re}}(n_{\text{TX}}) > E_{\text{re}}(n_{\text{RX}})$, calculate $E_{\text{re}}^{\text{avg}}$ and d_s^{avg}. Otherwise, decide to do non-CT and exit this procedure.
- **Step 2.** If num_trial is 1, set $cond$ as $COND_A$. If num_trial is 2, set $cond$ as $COND_B$. If num_trial is none of above, decide to do non-CT and exit this procedure.
- **Step 3.** n_{TX} decides possible cooperators (excluding n_{TX}) satisfying $cond$, and saves those nodes in the set S_{p}. If S_{p} is empty, set $num\_trial = num\_trial + 1$ and go to Step 2. If $|S_{\text{p}}| < N_c^{\text{opt}} - 1$, then $S_{\text{CT}} = \{n_{\text{TX}}, S_{\text{p}}\}$ and go to Step 6. Otherwise, set N_c=N_c^{opt} and proceed to the next step.
- **Step 4.** If $N_c = min(|S_{\text{p}}|, N_d)$, then $S_{\text{CT}} = \{n_{\text{TX}}, S_{\text{p}}\}$ and go to Step 6. If $|S_{\text{p}}| > N_c - 1$, the node n_{TX} forms S_{CT} ($|S_{\text{CT}}| = N_c$) by picking up $N_c - 1$ nodes from the set S_{p} that have the highest residual energies and itself. Otherwise, $S_{\text{CT}} = \{n_{\text{TX}}, S_{\text{p}}\}$.
- **Step 5.** Calculate d_{req} using (1) for the nodes in S_{CT}. Check the condition in (2). If (2) holds, decide to do CT and exit this procedure. If (2) does not hold, set $N_c = N_c + 1$ and go to Step 4.
- **Step 6.** Calculate d_{req} using (1) for nodes in S_{CT}. Check (2). If (2) does not hold, set $num\_trial = num\_trial + 1$ and go to Step 2. Otherwise, decide to do CT and exit this procedure.

III. Simulation Results

In this section, we provide simulation results for the REACT protocol. For the physical layer, we assume a Rayleigh fading channel with the path loss exponent of 3. The fading channel is slowly varying and remains same for the entire virtual MISO transmission (CT). For each N_c, we use the diversity gain in Table I. Also, we assume that the orthogonal diversity channel is obtained by a space-time block code (STBC), and the maximum number of orthogonal channels is 5 ($N_d = 5$). To calculate the energy consumption, we use the model and values in [17]. 128 bytes is used for the packet length. For diversity order larger than 2, full rate STBC does not exist [18]. The best achievable rate for the diversity order of 3 and 4 is 3/4, and, for the diversity order of 5, 2/3. This leads to additional energy consumption for N_c=3,4 and 5, which is included in the simulation.



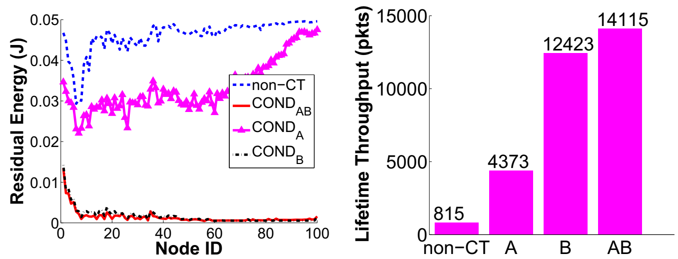
(a) Average residual energy after the network is dead for an 80m×80m network.

(b) Average lifetime throughput

Fig. 2. The simulation results comparing non-CT and REACT protocols.

The simulations are done for 4 different sizes of network: 40m×40m, 60m×60m, 80m×80m, and 100m×100m. The Sink is located at the bottom center of the network, and the network has 100 nodes having initial energy of 0.05(J) and a maximum single-transmit-node range of 20m ($d_{\text{tx}}^{\max} = 20$m). For non-CT routing, we consider two routing schemes: i) a routing scheme based on the smallest number of hops (Ad hoc On-demand Distance Vector (AODV) Routing [16]), and ii) an energy-aware routing scheme (Capacity Maximization (CMAX) Routing [12]). For REACT in Section II-D, we use these two non-CT routing schemes for setting up the primary route. The node ID of a node is assigned according to the proximity of the node to the Sink (the node closer to the Sink gets lower node ID). For each of the non-CT and REACT schemes, 20 trials are performed, and in each trial, the nodes are randomly relocated except for the Sink. The node closer to the Sink gets the lower node ID.

The simulation results are shown in Fig. 2. Fig. 2a shows the average residual energy results for each node after the network is dead for 80m×80m network. As can be seen from Fig. 2a, in the case of non-CT, the nodes close to the Sink (nodes with low node IDs) use more energy than the others. Fig. 2a also shows that CMAX tries to evenly distribute the loads close to the Sink, but the residual energies of the nodes far away from the Sink are close to their initial energies for non-CT cases, and these residual energies can be considered as wasted. In contrast, it can be observed that the REACT protocol well balances the energy. Balancing the energy is meaningless if it does not lead to the lifetime extension. The comparison of the lifetime throughput in terms of the total packets received at the Sink for 4 different sizes of network is shown in Fig. 2b. As can be seen from the figure, the lifetime extension achieved through REACT is significant. Because of the nature of the energy hole problem and the ability to spend unused energy by using REACT, for 80m×80m network, the extended lifetime when REACT is used is more than 16 times when AODV is used for both non-CT and REACT. When compared to CMAX, the extended lifetime when REACT is used is more than 5 times. Also, REACT with CMAX (REACT-CMAX) does not



(a) The average residual energy. (b) The average lifetime throughput.

Fig. 3. The effect of different conditions for CT decision.

show better performance than REACT with AODV (REACT-AODV). The reason for this is that CMAX is unaware of the CT option. Therefore, CMAX sometimes uses many more hops to go around the nodes that have low residual energy when a CT range extension would have used less energy. Since AODV itself has advantages over CMAX in terms of the complexity of the algorithm and number of hops, using REACT with AODV is a perfect choice in this case. Note that as the network size grows, the amount of the burden that the nodes in A_1 has to carry increases, and this means that the energy hole problem becomes more severe. Therefore, when the nodes in A_1 are a small fraction of the total and the energy hole problem becomes more critical, the lifetime extension achieved by REACT also increases. This is shown by the increase in the extended lifetime of REACT as the network size grows; the lifetime extension of REACT-AODV is more than 8 times the lifetime of CMAX for 100m$\times$100m, whereas when the energy hole problem is not critical (40m$\times$40m), the extended lifetime is less than twice.

Our algorithm successively checks for two conditions when deciding potential cooperators, S_{p}: $COND_A$ and $COND_B$. To see the effects of these conditions, we simulate the protocol using only one of the two conditions for 80m$\times$80m network. AODV is used for both non-CT and REACT, and 20 trials are performed. The average residual energies after the first node dies are shown in Fig. 3a, which shows four cases: i) non-CT, ii) REACT with only $COND_A$, iii) with only $COND_B$, iv) with both conditions as summarized in Section II-D ($COND_{AB}$). As can be seen from Fig. 3a, using condition $COND_A$, which is nearest to the optimal selection, does not consume unused energy as well as others. This is because this condition is too strict to gather enough cooperators to jump over the highly-burdened node and communicate with the Sink directly. Failure to do this leads to a poor performance on the lifetime throughput as shown in Fig. 3b ('A','B' and 'AB' indicate $COND_A$, $COND_B$ and $COND_{AB}$ respectively). The condition $COND_B$ alone successfully uses most of unused energy (Fig. 3a) and thereby gives a large lifetime extension compared to $COND_A$ alone (Fig. 3b). This shows that the effectiveness of our algorithm stems mostly from the ability to avoid highly-burdened nodes using the energies of the others, which are wasted if the highly-burdened nodes die early. Still, the lifetime extension can be improved further when both conditions are used as shown by 'AB' in Fig. 3b.

IV. Conclusion

In this paper, we have investigated the possibility of using CT with a range extension strategy to avoid the energy hole problem and extend the network lifetime of many-to-one multi-hop WSNs. We have designed a CT protocol, REACT, which regulates CT instances and selects cooperators, based on the residual energy. Because of the nature of the energy hole problem and the ability to use unused energy of the other nodes, REACT with AODV was shown to significantly extend the network lifetime (up to 8 times) compared to an energy-aware routing protocol (CMAX). REACT uses only the information of the neighbors, which makes the protocol simple and feasible. In addition, it can be built on top of any cross-layer framework designed to use cooperative transmission.

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