

Proposed Protocol: HEACT (Hybrid Energy-Aware Cluster-Tree)

The HEACT protocol is a hierarchical, energy-aware routing algorithm designed to improve network lifetime and stability in Wireless Sensor Networks (WSNs). It combines periodic clustering with an adaptive inter-cluster communication strategy. The protocol operates in rounds, punctuated by reconfiguration cycles.

A. Reconfiguration Cycle

Network reconfiguration (CH selection, cluster formation, and potentially inter-CH tree building) occurs periodically every $I_recluster$ rounds (e.g., 50 rounds), and also on the first round ($R=1$). A counter, $reconfig_count$, tracks the number of these cycles.

B. CH Selection (`select_heact_chs_refined`)

This refined process aims to select robust CHs, considering both energy and location:

1. **Eligibility:** Nodes must possess energy exceeding a minimum threshold (E_cand_thresh) to be considered candidates.
2. **Probability Calculation:** Each eligible node i computes its probability $T(i)$ of becoming a CH. This involves:
 - Calculating a base probability proportional to the node's share of the total current energy among all alive nodes ($BaseProb(i)$).
 - Calculating a distance modifier ($DistModifier(i)$) based on the node's distance to the BS relative to the average distance of all alive nodes. This modifier uses the D_factor parameter (e.g., 1.1) to slightly increase the probability for nodes located farther than average from the BS and decrease it for those closer.
 - The final probability is $T(i) = BaseProb(i) * DistModifier(i)$, clamped between 0 and 1.
3. **Election:** Each eligible node selects a random number; if it's less than $T(i)$, the node becomes a CH for this cycle.
4. **Fallback:** If no CHs are elected probabilistically, the eligible node with the highest remaining energy is designated as a CH to ensure network functionality.

C. Cluster Formation (`form_heact_clusters`)

After CHs are selected:

1. **Advertisement (Implicit):** CHs make their status known.
2. **Member Association:** Non-CH nodes identify the nearest *alive* CH.
3. **Cluster Size Limit:** Before joining, the target CH verifies if its current number of members is below the maximum allowed size (C_max_size).
4. **Joining:** If the CH has capacity and energy checks for control packet exchange pass, the node joins the cluster. The CH records the member and updates its size count. Nodes unable to join a non-full, alive CH remain unclustered for the cycle.

D. Inter-CH Tree Formation (`build_inter_cluster_tree_heact_further_revised`)

This crucial step establishes the multi-hop routing backbone between CHs and is executed only **after** an initial stabilization period ($\text{reconfig_count} > I_direct$, e.g., after 3 reconfiguration cycles).

1. **Relay Eligibility:** Only CHs with energy exceeding a specific relay threshold (E_relay_thresh) can serve as parent nodes (relays) in the inter-CH tree.
2. **Root Selection:** The algorithm identifies the CH closest to the BS among those meeting the relay energy threshold. This CH becomes the primary root, linking directly to the BS. If no CH meets the threshold, the absolute closest CH connects to the BS but cannot act as a relay.
3. **Iterative Tree Construction:** Remaining CHs are added iteratively:
 - For each unvisited CH (q_ch), potential parents (i_ch) are evaluated from the set of CHs already in the tree *that are eligible relays*.
 - **Energy-Penalized Cost:** The cost for q_ch to connect via i_ch is calculated using:

$$\text{Cost} = (\text{LinkCost} + \text{ParentPathCost}) * \text{EnergyPenaltyMultiplier}$$
 where LinkCost is based on the squared distance $d(q_ch, i_ch)^2$, ParentPathCost is the accumulated cost from i_ch to the BS (stored in $i_ch.\text{path_cost_sq_ch}$), and EnergyPenaltyMultiplier is $(1.0 / \max(0.01, \text{EnergyRatio}(i_ch))) ** P_exp$. The EnergyRatio is the parent's current energy relative to its initial energy, and P_exp (e.g., 1.5) controls how steeply the cost increases for parents with lower energy.
 - **Parent Selection:** q_ch chooses the eligible parent i_ch that minimizes this weighted cost.
 - **Tree Update:** The link is formed, the weighted cost is stored for q_ch , and q_ch itself becomes a potential parent for future iterations *only if* it meets the E_relay_thresh .
4. **Termination:** The process ends when all CHs are connected or no further connections can be made via eligible relay parents.

E. Steady-State Data Transmission ($\text{simulate_heact_steady_state}$)

Data transfer occurs in every round between reconfigurations:

1. **Intra-Cluster:** Member nodes send data packets to their CH.
2. **CH Aggregation:** Each CH aggregates received member data with its own.
3. **CH Transmission (Dual-Mode):**
 - **Initial Direct Phase ($\text{reconfig_count} \leq I_direct$):** CHs transmit aggregated packets directly to the BS.
 - **Tree Phase ($\text{reconfig_count} > I_direct$ and tree was built):** CHs transmit aggregated packets along the inter-CH tree. Transmissions follow a leaf-to-root order. Each CH sends its packet (own + members + received from child CHs) to its designated parent. If the parent is another CH, it receives, aggregates further, and forwards; if the parent is the BS, the data delivery is complete for that branch.

This refined HEACT algorithm aims to enhance network stability by protecting nodes during the initial rounds via direct CH transmission and cluster size limits, while promoting long-term efficiency through energy-aware CH selection and robust, energy-penalized inter-CH tree routing in later phases.