ORCHID: Tessellation-Based Cylindrical Deployment Protocol for Energy-Efficient Coverage in Three-dimensional Wireless Sensor Networks

David W. Starr [1] and Habib M. Ammari [2]
[1] Wertheim College of Engineering, University of Florida, Gainesville, FL 32611, USA
[2] Wireless Sensor and Mobile Autonomous Networks (WiSeMAN) Research Center
School of Engineering
College of Arts and Sciences
Texas A&M International University, Laredo, TX 78041, USA
david.starr@ufl.edu, Habib.Ammari@tamiu.edu

***Abstract*—Wireless Sensor Networks (WSNs) play a critical role in environmental monitoring, surveillance, and battlefield communications. There has been an increasing demand for WSNs that optimize network lifetime and energy consumption, a critical design challenge. Previous research has made use of two separate optimization paths: global deployment geometry to reduce communication costs to transmit to the Base Station (BS), or optimization of local network topology to improve routing efficiency. In this paper, we introduce the Optimal Rhombic Cylindrical Hybrid Intelligent Deployment (ORCHID) protocol that will synergize the two optimization paths. ORCHID operates by considering tessellation within a geometrically optimized cylinder. This structure enables an intelligent protocol architecture, featuring a deterministic, energy-aware cluster head selection process that replaces probabilistic mechanisms found in other protocols. We will compare the performance of this protocol to a previously proposed cylindrical LEACH implementation. Through simulations, ORCHID shows improvements in network lifetime, cumulative throughput, and energy consumption. The protocol has very low overhead, which will be scaled along with performance to compare to the most recent similar protocols such as PEG-GA-VC(3) (2019), a Hybrid k-means clustering algorithm (2017), and LEACH3D (2015).**

***Index Terms*—Wireless sensor networks, coverage, clustering, rhombic cylindrical deployment, tessellation.**

I. Introduction

Wireless sensor networks (WSNs) are viable in many applications, including emergency relief, environmental monitoring, and battlefield communications [1], [2]. WSNs are constrained by the finite energy of sensor nodes, requiring low energy consumption and extensive network lifetime to deliver proper results and efficiency for applications [3]. This becomes challenging when considering that these characteristics must be maintained along with full volumetric connected coverage.

A. Problem Statement and Motivations

Clustering protocols are common solutions, effectively organizing the network into manageable groups to extend network lifetime and reduce energy consumption. However, most of these protocols suffer from uneven cluster distribution due to probabilistic cluster head (CH) selection, as well as the "hotspot" problem, where nodes closer to the BS use all energy prematurely by relaying packets for the entire network [4], [5]. Other solutions involve the use of tessellation with polyhedral shapes that leave no gaps or overlaps in space [6]–[9]. However, these solutions largely assume cubic deployment fields, have high computational overhead, and have weak integration with energy models and energy efficiency. To address these complications, research has progressed along two separate optimization paths. The first is centered on global deployment geometry, with work done [2] demonstrating that deploying nodes within an optimally-proportioned cylinder minimizes the average CH-to-BS communication energy compared to a standard cubic network. The second path is centered on local network topology, showing that structured tessellations can improve routing efficiency and coverage compactness [6]. These optimization strategies have not been synergistically used in an effective protocol, leaving an unaddressed gap in literature. In this paper, we bridge the gap by introducing the Optimal Rhombic Cylindrical Hybrid Intelligent Deployment (ORCHID) protocol. This protocol integrates the two research areas by using tessellation with rhombic dodecahedra (RD) within a geometrically optimal cylinder. This structure will enable a deterministic energy-aware CH selection mechanism and will replace the commonplace probabilistic nature of other protocols. The network's spatial awareness will also be used to implement a two-zone relay routing scheme that mitigates the hotspot problem by reducing strain on any particular node and avoiding costly long-range transmissions.

B. Major Contributions

The major contributions of this paper can be summarized as follows: leftmargin=*, topsep=1pt, itemsep=0pt, parsep=0pt

- We demonstrate that the integration of global deployment geometry optimization and local topology optimization (tessellation) using ORCHID effectively reduces energy consumption and enhances network lifetime.

- We compare common network metrics between ORCHID and a previously proposed cylindrical implementation of the LEACH protocol.
- We scale overhead and performance to compare ORCHID to the most recent clustering protocols that maintain similar assumptions (PEG-GA-VC(3), Hybrid K-means, and LEACH3D). This demonstrates ORCHID's improved performance to overhead ratio.

II. Related Work

Energy efficient protocol design in WSNs has been extensively studied in literature, with clustering being a primary strategy. The LEACH protocol [3] established a foundational concept of rotating CHs to distribute energy load. Subsequent work like HEED [4] improved CH selection by incorporating residual energy and node proximity, while TEEN and APTEEN adapted clustering for reactive networks [10], [11]. Further, protocols like M-LEACH, Q-LEACH, and EECDA extended LEACH to address mobility, QoS, and coverage awareness. [12]–[14]. When considering three-dimensional and spatially sensitive clustering, 3D-LEACH used three-dimensional Euclidean distances for CH selection [15]. Regarding tessellation, Mishra and Gore determined the optimal space paver for coverage [6], while other work includes using Voronoi tessellation to ensure connectivity and sensing coverage [16]. However, many existing variants have high overhead, neglect global deployment, and use probabilistic mechanisms.

III. Network and Energy Models

We model a three-dimensional (3D) WSN with N static nodes uniformly distributed within a cylindrical Domain of Interest (DoI) of height H and radius R. For optimizing global geometry and energy efficiency, the cylindrical deployment will be constrained to the aspect ratio of $R = 0.684H$ [2]. A single BS that is not constrained by energy is located at the centroid (0,0,0). We assume the network is dense enough for full coverage and that the communication range (R_c) is at least twice the sensing radius (R_s), ensuring connectivity. Energy consumption will be quantified using the first-order radio energy model [3]. The model accounts for transceiver and amplifier energy, distinguishing between short-range (free space, d^2) and long-range (multi-path, d^4) transmissions based on a crossover distance (d_0). The key parameters used are listed in Table 1.

IV. Geometric Foundations of ORCHID

The benefits of the ORCHID protocol are supported and informed by a quantitative analysis of both local and global network geometry. We will present the core mathematical derivations for the use of RD for local tessellation and an optimally proportioned cylinder for global deployment volume.

TABLE I: NETWORK AND ENERGY MODEL NOTATION

Parameter	Description
Network Parameters	
H, R	Height and Radius of the deployment cylinder
N	Total number of sensor nodes
BS	Base Station position
Node Parameters	
E_o	Initial energy of a sensor node
r_s	Sensing radius of a node
R_c	Communication radius of a node
Energy Model Parameters	
E_{elec}	Energy consumed by transceiver electronics per bit
E_{DA}	Energy consumed for data aggregation per bit
ϵ_{fs}	Amplifier coefficient for the free-space model (d^2)
ϵ_{mp}	Amplifier coefficient for the multi-path model (d^4)
k	Packet size in bits
d_o	Crossover distance between energy models

A. Local Topology Efficiency

The first metric considered is coverage resilience. This quantifies a paver's tolerance for a reduction in sensing range before coverage is lost at any vertex on the paver. We define the following lemma to support:

Lemma 1: Among common 3D pavers, the RD offers the highest coverage resilience.

Proof: For pavers like the cube, where all vertices are equidistant from the centroid, the resilience is 0%. For the RD, its 6 outer vertices lie on the circumsphere (R_{RD} = a), while its inner 8 vertices are at a closer distance of $d_{\text{inner}} = \left(\frac{\sqrt{3}}{2}\right) a$. The resilience can be calculated by determining the normalized difference between the vertices:

$$\begin{aligned} \text{Resilience} &= \frac{R_{RD} - d_{\text{inner}}}{R_{RD}} \\ &= \frac{a - \left(\frac{\sqrt{3}}{2}\right) a}{a} \\ &= 1 - \frac{\sqrt{3}}{2} = 13.4\% \end{aligned} \tag{1}$$

The cube, truncated octahedron, and hexagonal prism, other common pavers, all have vertices that lie on their circumspheres, making their resilience 0%. Next we will consider the average hop count for inter-cluster routing.

Lemma 2: The RD lattice minimizes the average hop count for inter-cluster routing.

Proof: The average hop count, defined as $\bar{H}_i$, is inversely related to the paver's coordination number (amount of face-adjacent neighbors). The RD lattice has a coordination number of 12, which allows for isotropic 3D movement. The cube and the hexagonal prism, 6 and 8 neighbors, have lower coordination numbers and more restrictive movement. This concept establishes the strict ordering for average hop count:

$$\bar{H}_{RD} < \bar{H}_{HP} < \bar{H}_{\text{Cubic}} \tag{2}$$

The RD provides the most efficient routing support. We can now establish the following theorem:

Theorem 1: A routing protocol using RD tessellation will minimize local routing energy.

Proof: The total energy for routing a packet over H hops, where each hop has a constant inter-cluster distance (d_{const}) is a function of the hop count:

$$E_{\text{route}} = (H-1) \cdot [2k \cdot E_{\text{elec}} + k \cdot \epsilon \cdot d^{\alpha}_{\text{const}}] \tag{3}$$

Based on local routing energy being a function of hop count, and Lemma 2 proving that the RD minimizes H, it follows that the RD minimizes the routing energy to other pavers:

$$E_{\text{route}, RD} < E_{\text{route}, HP} < E_{\text{route, Cubic}} < E_{\text{route}, TO} \tag{4}$$

Note that the truncated octahedron (TO) was stated to have the highest energy due to complexities with routing between its two different hop distances. This is also why it was omitted from Lemma 2.

B. Global Geometry Optimization:

We now prove that a cylinder (geometrically optimized) is the most energy efficient deployment volume. We define the following lemma to support:

Lemma 3: For a fixed volume V, the mean squared Euclidean distance and mean biquadratic distance is lower in an optimally-proportioned cylinder than in a cube.

Proof: We compare the mean squared Euclidean distance ($\mathbb{E}[d^2]$) for both shapes. For a cube with a side length defined as L and a volume where $V = L^3$, the mean squared distance is derived from the triple integral over the volume:

$$\mathbb{E}[d^2_{\text{cube}}] = \frac{1}{V} \int_{-L/2}^{L/2} \int_{-L/2}^{L/2} \int_{-L/2}^{L/2} (x^2 + y^2 + z^2)\, dx\, dy\, dz \tag{5}$$

This integral is separable, and we solve for the x^2 term:

$$\begin{aligned} \iiint x^2\, dV &= \int_{-L/2}^{L/2} x^2\, dx \int_{-L/2}^{L/2} dy \int_{-L/2}^{L/2} dz \\ &= \left[\frac{x^3}{3}\right]_{-L/2}^{L/2} \cdot L \cdot L \\ &= \frac{L^5}{12} \end{aligned} \tag{6}$$

By symmetry, the integrals for both y^2 and z^2 yield the same result. The expression for mean squared distance (cubic) is:

$$\begin{aligned} \mathbb{E}[d^2_{\text{cube}}] &= \frac{1}{L^3} \left(\frac{L^5}{12} + \frac{L^5}{12} + \frac{L^5}{12} \right) \\ &= \frac{3L^5}{12L^3} \\ &= \frac{L^2}{4} \end{aligned} \tag{7}$$

In terms of volume, V, this is:

$$\mathbb{E}[d^2_{\text{cube}}] = 0.25\, V^{2/3} \tag{8}$$

For a cylinder, we find the optimal aspect ratio by minimizing the maximum squared distance:

$$C = R^2 + \left(\frac{H}{2}\right)^2 \tag{9}$$

Subject to the spherical constraint:

$$V = \pi R^2 H \tag{10}$$

Setting the derivative with respect to C yields the polynomial:

$$8R^4 - 2R^2H^2 - H^4 = 0 \tag{11}$$

Solving this yields the optimal ratio that is similar to the one proposed by Jaradat et al. (Differences attributed to the slightly different calculation techniques) [2].

$$R = 0.707H \tag{12}$$

Using the ratio $R = 0.684H$ [2] for comparison, the mean squared distance in the cylinder is:

$$\begin{aligned} \mathbb{E}[d^2_{\text{cyl}}] &= \frac{R^2}{2} + \frac{H^2}{12} \\ &= 0.3172\, H^2 \end{aligned} \tag{13}$$

Relating this to volume ($H^2 = 0.77\, V^{2/3}$), we then find:

$$\begin{aligned} \mathbb{E}[d^2_{\text{cyl}}] &= 0.3172 \left(0.77 V^{2/3}\right) \\ &= 0.244\, V^{2/3} \end{aligned} \tag{14}$$

Since $0.244\, V^{2/3} < 0.25\, V^{2/3}$, the cylinder has a lower mean squared distance. We now define Theorem 2:

Theorem 2: The average transmission energy from a CH to a central BS is minimized by using an optimal cylindrical deployment volume.

Proof: The transmission energy (E_{TX}) is directly proportional to a power of the distance (d^{α}). Minimizing the average energy is then achieved by minimizing the average distance moments, $\mathbb{E}[d^2]$. As shown in Lemma 3, an optimal cylinder minimizes this distance compared to a cube. Therefore, the energy is minimized in an optimal cylindrical deployment.

Algorithm 1 ORCHID Per-Round Protocol Logic

Input: Set of all nodes S, Set of RD regions $\mathcal{T}$, Crossover distance d_o.
Output: Aggregated data packets delivered to Base Station (BS).
Phase 1: Deterministic CH Selection
$CH_{set} \leftarrow \emptyset$
for each region $T_j \in \mathcal{T}$ **do**
  $CandidateNodes \leftarrow \{s \mid s \in T_j$ and $s.cooldown ==$ false$\}$
  if $CandidateNodes$ is not empty **then**
    $selected\_CH \leftarrow \arg\max_{s \in \text{CandidateNodes}}(s.\text{energy})$ $\{O(N_j)$ per region$\}$
    $CH_{set} \leftarrow CH_{set} \cup \{selected\_CH\}$
  end if
end for
Phase 2: Cluster Formation & Aggregation
All non-CH nodes join the nearest CH in CH_{set}. $\{O(1)$ per node$\}$
All CHs in CH_{set} aggregate data.
Phase 3: Inter-Cluster Relay Routing
for each $current\_CH \in CH_{set}$ **do**
  if distance$(current_CH, \text{BS}) \leq d_o$ **then**
    `Transmit`(data, BS, low_cost_d^2_model)
  else
    $optimal\_relay \leftarrow$ FindOptimalRelay$(current_CH)$
    if $optimal\_relay$ is not NULL **then**
      Transmit(data, opt_relay, low_cost_d^2_model)
    else
      Transmit(data, BS, high_cost_d^4_model) {Last resort}
    end if
  end if
end for

V. Optimal Rhombic Cylindrical Hybrid Intelligent Deployment

The ORCHID protocol operates within an optimal cylindrical volume ($R = 0.684H$), partitioned by a RD tessellation. These RDs serve as immutable cluster regions, providing a stable, predictable structure. The protocol's core is a two-zone relay system based on the radio model's crossover distance (d_0), which creates a low-cost "safe-zone" and a high-cost "far-zone". A "Virtual Guard Band" solution supports this by pre-classifying cells as "interior" or "boundary" to solve the geometric problem of clipped cells and ensure reliable pathing. ORCHID has two phases. The one-time setup is performed by the energy-unconstrained base station, which offloads all heavy computation from the sensor nodes. During this phase, the base station first partitions the volume with the RD tessellation and then assigns each node to its nearest RD cell centroid. Finally, it performs the "Virtual Guard Band" classification, flagging any cell with a neighbor outside the cylinder as a "boundary" cell. Anything not considered a "boundary" cell is considered as "interior". The round-based steady-state phase begins with deterministic CH selection. In each cell, the node with the highest remaining energy becomes the CH. After cluster formation and data aggregation, CHs execute the boundary-aware relay routing. If a CH is in the "safe-zone", it transmits directly to the BS using a low-cost (d^2) model. If in the "far-zone", it queries its 12 neighbors for a relay, using the pre-computed classifications to prioritize interior over boundary cells. If a suitable relay is found, the same low-cost model is used; otherwise, it transmits directly using a high-cost (d^4) model as a last resort. This logic is provided in detail by Algorithm 1.

VI. Performance Evaluation

In this section we will analyze the efficiency of the ORCHID protocol and its characteristics. Our simulations are based on the widely used first order radio energy model, consistent in other works and protocols. This approach, despite not considering physical and MAC layer complexities like packet loss and channel fading, has been chosen intentionally. This allows for a direct evaluation of performance based on the primary contributions of the protocol to global deployment geometry and local topological efficiency. Isolation of these factors allows us to attribute gains to the core mechanics of the ORCHID protocol itself, allowing for fair comparison.

A. Analysis of Stability and Overhead

To holistically evaluate protocols beyond singular metrics, we define a trade-off between stability and overhead. One strength of ORCHID is its stability combined with its low overhead. We will compare it with an energy efficient hybrid k-means algorithm [17], PEG-GA-VC(3) [18], and LEACH3D [15]. We define a trade-off that will be used to compare the stability and overhead of the protocols. The slope of the network lifetime graphs represent the rate at which nodes fail, an indicator of network stability. We first calculate the Normalized Decay Rate (NormDR). This defines the fraction of the total network that fails per round, scaled accordingly to make it comparable. It is defined as follows:

$$\text{NormDR} = \frac{|\Delta\text{Nodes} \,/\, \Delta\text{Rounds}|}{N} \tag{15}$$

Stability is not free, and is achieved through algorithms that impose high computational overhead on the nodes. This overhead consumes energy. To quantify this, we introduce the Overhead Complexity Factor (OCF). This is derived from the asymptotic complexity of a protocol's network organization phase conducted per-round by sensor nodes. This is an established computer science principle for classifying computing cost. An order of magnitude factor is assigned to represent distinct classes of complexity. **OCF = 1 (Static/Low Complexity)** contains protocols where the pre-round network organization is simple and a constant time $O(1)$ operation, like ORCHID and LEACH3D. **OCF = 100 (High Iterative Complexity)** contains protocols relying on iterative algorithms, such as hybrid k-means with its $O(N \times C \times I)$ complexity. **OCF = 1000 (Very High Evolutionary Complexity)** contains protocols that use intensive metaheuristics such as genetic algorithms. The PEG-GA-VC(3) protocol falls under this category, using a genetic algorithm where the complexity is modeled as $O(G \times P \times n_c)$. We combine these two into a final figure defined as the Stability-Overhead Score (SOS). This is similar to figures of merit such as Power-Delay-Product. It is defined as:

$$\text{SOS} = \frac{\frac{1}{\text{NormDR}}}{\text{OCF}} \tag{16}$$

The reciprocal of NormDR is taken so higher stability increases the score. We divide by OCF to penalize overhead. Figure 1 shows the comparison of SOS for the four protocols. With an SOS of 870, ORCHID decisively outperforms its peers, demonstrating a proper balance between performance and overhead. While complex protocols achieve high stability, they are penalized by overhead, resulting in scores 25 times lower than ORCHID's. These metrics were considered using the most simple parameters and scaled as if each of the protocols were using 100 nodes in the simulation.

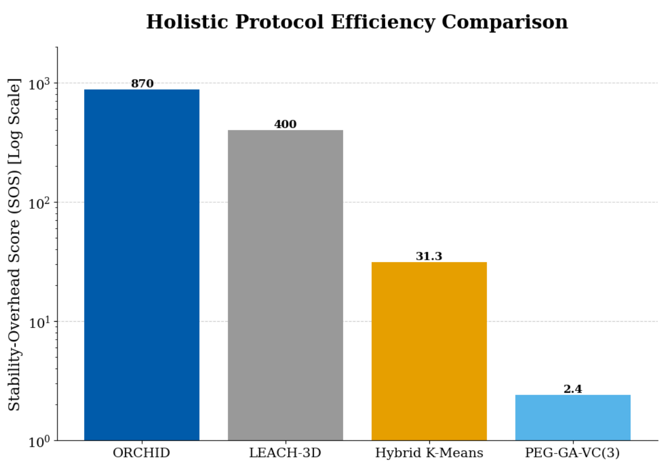

Fig. 1: SOS score comparisons for the protocols.

B. Simulation Setup and Results

To ensure a fair comparison to Jaradat et al.'s [2] cylindrical implementation (one of few focusing on cylindrical deployment, we will the same simulation metrics. They are provided by Table 2. These metrics were chosen to align with common standards in WSN protocols. These are standard considerations used in many different LEACH variations, with the network size chosen to demonstrate the scalability of the protocol in a dense network environment. Based on these parameters, four simulation metrics will be compared. They are network remaining energy, network lifetime, cumulative throughput, and average CH to BS transmission energy. The other protocol will be referred to as "LEACHJ" for simplicity on the graphs.

The simulation results (Fig. 2-5) demonstrate ORCHID's quantifiable improvements across all key metrics. As seen in Figure 2, ORCHID retains twice as much network energy as LEACHJ after 500 rounds (20 joules vs. 10 joules), a direct result of its ability to prevent energy hotspots through intelligent relaying. When comparing network lifetime and First Node Death (FND) in Figure 3, the LEACHJ value had a reported value of 72, compared to the improved FND of 101 for ORCHID. More significantly, the post-FND stability highlights ORCHID's superior load balancing. As the network continues running, nodes die faster in the LEACHJ implementation than in ORCHID. The improvement results in a 93% improvement in half node death; it takes

TABLE II: SIMULATION PARAMETERS USED IN THE NETWORK EVALUATION

Parameter	Value
E_0	0.5 J
E_{elec}	50 nJ/bit
E_{DA}	5 nJ/bit
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
k	500 Bytes
V_{cyl}	V_{cub}
N	200
P	0.1
Rounds	2000

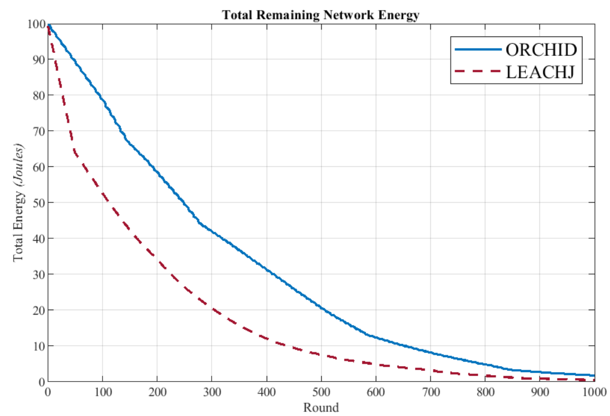

Fig. 2: Total remaining network energy comparison

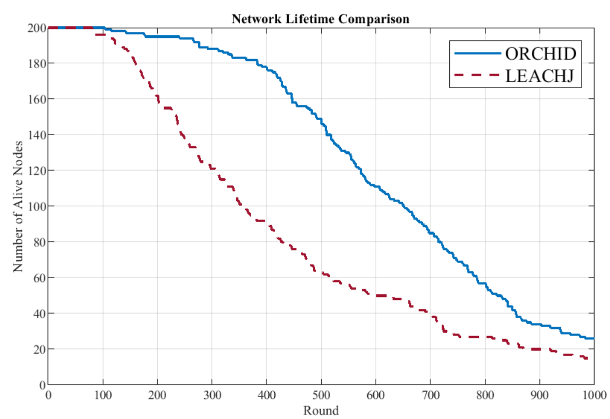

Fig. 3: Network lifetime comparison for the protocols.

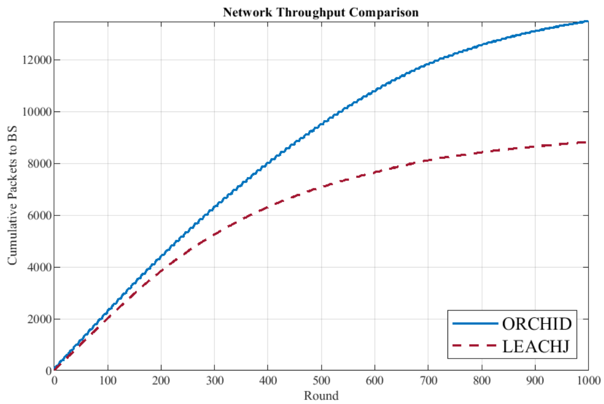

Fig. 4: Cumulative throughput comparison.

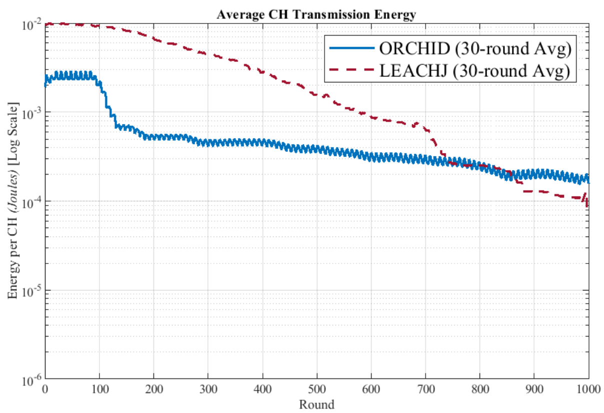

Fig. 5: Average CH to BS transmission energy comparison.

ORCHID 800 rounds to drop to the same level of nodes that LEACHJ reaches in 500 rounds. This increased stability also leads to the improved throughput shown in Figure 4. Since ORCHID keeps more nodes alive for longer, it is able to deliver around 14,000 packets over the duration of the simulation, an improvement of over 50%. ORCHID effectively provides a sustained, high rate of data delivery for the majority of its operational life, whereas LEACHJ shows diminishing returns as its network degrades. Figure 5 shows that ORCHID also maintains a consistently lower average energy per CH transmission compared to LEACHJ. This is the core of its efficiency. Although LEACHJ's average appears to drop below ORCHID's after 750 rounds, this is attributed to high-energy nodes having already been depleted from the network. ORCHID avoids this problem by maintaining lower overall transmission costs during the network's most critical operational period. These benefits can be attributed to ORCHID's two-zone relay routing mechanism, optimal geometric deployment, and deterministic load balancing across all nodes.

VII. Conclusion

In this work, we introduced ORCHID, a protocol for 3D WSNs that combines global deployment geometry with local network topology. By integrating an RD tessellation within an optimally-proportioned cylinder, ORCHID establishes a predictable network structure that enables deterministic CH selection and a two-zone relay routing mechanism to mitigate the hotspot problem. Through simulation, we demonstrated ORCHID's quantifiable improvements in lifetime, throughput, and energy efficiency over a standard LEACH protocol. We also introduced the Stability-Overhead Score (SOS), a holistic metric showing ORCHID's low-overhead design outperforms more complex protocols. Future work will extend the ORCHID framework to support mobile and heterogeneous sensor networks.

VIII. Acknowledgment

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