Energy-Aware Spread Deployment of Drone Swarms under a Battery Budget

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***Abstract*—A swarm of drones can provide coverage over an area where no infrastructure exists, but each drone flies on a finite battery and must periodically return to a base to recharge before redeploying. This paper establishes what that single constraint imposes on a swarm that is spreading out. We study a local rule under which a drone advances one cell per round using only its immediate neighbourhood, and returns to the base once its charge falls below a reserve. Because a drone must keep enough charge to fly home, that round trip halves the distance at which it can settle. Its battery therefore caps its reach, and that cap is independent of the swarm size: covered area saturates, and beyond a threshold additional drones extend it no further. The reach is instead determined by the way capacity is distributed across the swarm. Holding the swarm's total capacity constant and varying only its sharing, we show that an uneven sharing carries the swarm measurably further: past the saturation size, where an added drone buys nothing, the same total capacity shared unevenly among the same drones raises the reach by up to 75% and the covered area by up to 79%. We also derive the furthest ring such a sharing can reach, by matching rings to batteries. The local rule attains most of it without ever reading a battery level: a drained drone stops and a fresh one passes it, so the swarm sorts itself by capacity.**

***Index Terms*—drone swarm; self-deployment; area coverage; energy constraint; battery; recharge; network lifetime; hexagonal grid; coverage control**

I. Introduction

When infrastructure is absent or destroyed, a swarm of small drones is often the only means of covering an area. The task such a swarm repeats is *self-deployment*: starting from a base, it spreads out to cover the area while remaining connected and compact. Many distributed rules achieve this [1, 2], and nearly all of them assume that motion is free, so that a drone may reposition without limit. Real drones cannot. They fly on a finite battery, expend energy both to move and to remain in place, and must return to a base to recharge [3]. The gap matters most in the settings where such swarms are useful, since a search or a watch is measured in hours rather than minutes. Coverage is then not a property of the final formation, but a quantity the swarm must sustain while its members keep leaving their posts.

The first practical question is whether a small battery can be offset by deploying more drones. It cannot, and the reason is geometric rather than algorithmic. A drone flying outward must retain enough charge to return, so the mandatory round trip halves the distance at which it can settle. That limit follows from a single drone's budget and contains no swarm size, so adding drones does not move it. Beyond a threshold, additional drones thicken what is already covered or fail to arrive, and the covered area ceases to grow.

The reach is instead determined by the way capacity is distributed across the swarm, and establishing that is the contribution of this paper. Batteries age unequally, so each drone carries its own charge and has its own ceiling. Holding the swarm's total capacity constant and varying only its sharing, we show that an uneven sharing carries the swarm measurably further. We measure this past the saturation size, where an added drone buys nothing: there, the same total capacity shared unevenly among the same drones raises the reach by up to 75% and the covered area by up to 79%. We also derive the furthest ring such a sharing can reach, by matching rings to batteries. The rule attains most of it without ever reading a battery level: a drained drone stops and a fresh one passes it, so the swarm sorts itself by capacity. All of this holds within one regime, that of sustained coverage from a *single* base with a mandatory return; several bases, mobile chargers and battery swaps [4, 5] relax it, and Section VI returns to them.

Organisation. Section II places the work and Section III gives the model. Section IV derives the two ceilings and the saturation size; Section V measures them, and what unequal batteries do. Sections VI and VII state the limits and conclude.

II. Related work

Energy-aware deployment. Energy is now a first-class variable in UAV networking. Closed-form rotary-wing propulsion models with an explicit hover term [3, 6] justify billing a drone for both displacement and station-keeping. That line optimises a *static* energy-efficient configuration rather than the energy *dynamics* of a swarm that keeps spreading and returning to recharge. Our spread rule itself belongs to the local coverage-control tradition [1, 2], which assumes motion is free; when that assumption holds, coverage holes are healed by generic geometric criteria, with no account of the energy each repair costs.

Persistent coverage with recharge. Where classical sensor-network work stretches lifetime by duty-cycling *static* nodes, persistent-coverage work sustains a moving team through recharge logistics or return-to-base scheduling [7, 8], and its recent line moves the charger rather than the schedule, pairing

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energy-constrained UAVs with mobile charging stations or a recharging ground vehicle [4, 5]. In all of these the monitored *targets or routes are fixed*, and the effort goes into scheduling. *Our gap.* The closest work bounds the cost of *persistence* for *fixed* targets. Asghar et al. [8] give the minimum swarm size meeting per-vertex latency under a discharge time; Qin et al. [9] derive, via stochastic geometry, a coverage probability that *saturates* with battery and charger density. None of these derives a *reach* bound for an outward-spreading *area* swarm: their targets are pre-placed, so the reachable distance is an input, not an output, and saturation appears as an averaged probability rather than a deterministic ring, reached by a swarm whose size the theory predicts. We supply exactly that object. Closest to our heterogeneity result, Zhang et al. [10] observe that a swarm's coverage lifetime is set by the *minimum* leftover energy rather than the total energy; we show the dual effect on *reach*, where it is the upper tail of the capacity distribution that decides.

III. Model: Energy-Aware Spread

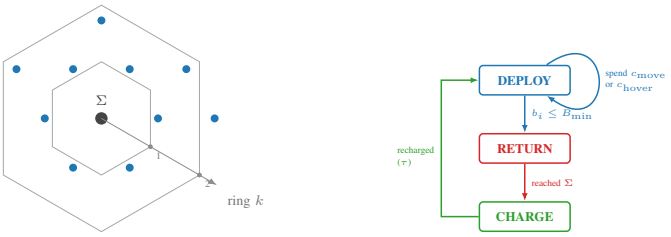
We build on a local, target-free *spread* rule for self-deployment, of the kind studied in distributed coverage control [1, 2]. We take that rule as given, specify it below, and add a battery layer on top. Every symbol is introduced where it is first used.

Space and spread rule. Space is a hexagonal grid. A cell's *ring* is its hop-distance to the base Σ, so ring k has $6k$ cells. Two drones are connected when they occupy the same or adjacent cells. All N drones start co-located at Σ, the *grouped start* of classic distributed heuristics. Each round every drone either stays or steps to one of its six neighbours, seeing only its own cell and those neighbours: a purely local, target-free view. It prefers a less crowded, more outward cell. Because the highest-priority drone on any occupied cell never leaves, this "never vacate a cell" invariant keeps the swarm connected in the energy-free world.

The assumption broken by energy. The connectivity guarantee rests on *nobody ever leaving a cell*. A drone that must return to the base to recharge *does* leave. Holes open in the deployed topology, and the guarantees of the energy-free world become quantities to measure.

Battery and states (Fig. 1). Every drone carries a battery $b_i \in [0, B]$ and is in one of three states. In DEPLOY it runs the spread rule and spends c_{move} to move one cell, or $c_{\text{hover}} > 0$ to hover. Once $b_i \le B_{\min}$ it switches to RETURN and flies straight back to Σ, one ring inward per round (still paying c_{move}). At the base it CHARGEs for τ rounds and then redeploys. We normalise $c_{\text{move}} = 1$, so B counts cells of travel per charge. Our defaults are $B = 20$ and $c_{\text{hover}} = 0.05$. One synchronous round runs in four steps: drones below the threshold switch to RETURN; returning drones step one ring inward; recharged drones re-enter DEPLOY; the rest take one spread step.

Swept variants. The return threshold $B_{\min}$ is swept as *fixed* ($= r$), *proportional* ($= kc_{\text{move}}$, "keep enough to return from ring k") and $\max(r, kc_{\text{move}})$. Recharge is swept as *full* ($b_i \leftarrow B$ after τ), *percent* (a fixed fraction of B instead of a full refill) and *instant* (a waiting pool, $\tau = 0$). Unless stated otherwise we use the proportional/full pair.



(a) Grid, base and rings. (b) Life-cycle of a drone.

Fig. 1: The energy-aware spread: grid and rings on the left, a drone's life-cycle on the right.

Return safety. A threshold rule is meaningful only if a drone that trips it can return. A drone never takes an outward step that would leave it below the return reserve of the cell it lands on, and a returning drone whose battery empties before the base is *stranded*, lost for good. Under the *proportional* and *max* thresholds the reserve equals the ring's return cost by construction, so no drone is ever stranded, and we verify it: zero in every run. Under a *fixed* reserve r a drone beyond ring $\lfloor r/c_{\text{move}} \rfloor$ cannot pay for the trip home and strands, which is why the fixed case of Prop. 1 is a *one-way* reach, well posed only when the reserve is large enough to fly home from the furthest reachable ring.

Scope of the energy budget, and its single free ratio. Only flight is billed: moving and staying in place, the two terms multirotor power models identify as dominant [3, 6]. Avionics, sensing, computing and radio are not modelled, and the direction of that omission is known: they would drain the battery without buying distance, so a real drone reaches no further than ours and the reach ceiling of Section IV stays an *upper* bound. Their form is harmless too, since to first order they are a constant draw per round, which is what c_{hover} already is. The one physically meaningful parameter is therefore the ratio $c_{\text{hover}}/c_{\text{move}}$; everything else is a normalisation.

We are explicit about that ratio because it is the only quantity a reader could contest. Ours is 0.05, and it is optimistic: on a rotary-wing platform, hovering and slow forward flight draw power of the same order, so a calibrated value would sit nearer 1. Every *ceiling* in this paper is free of it: how far out a drone can go and still come home, how far out it can hold a position rather than merely touch it, and how far an unequally equipped swarm could reach, are all built from B and c_{move} alone. None of the three contains c_{hover}.

What the ratio governs is instead the *time* a drone can hold a position. Once its round trip is paid for, a drone on ring k has $B - 2kc_{\text{move}}$ left, so it can stay $(B - 2kc_{\text{move}})/c_{\text{hover}}$ rounds, and that number collapses as the ratio grows. Two things follow. Each drone spends a smaller share of its life on station, so keeping the sustainable disc covered takes more of them: the swarm size past which added drones stop enlarging the covered area, derived in Section IV, rises from 316 at our

ratio to 609 at a ratio of one. And a large battery buys the ability to *get* to a far ring rather than to *stay* on it, so which sharing reaches furthest depends on the ratio too; we claim no ordering there.

IV. Analysis: the geometry of the energy budget

A battery budget turns coverage into a *geometric* problem, with no probability and no optimisation. Three quantities follow from it by elementary algebra: the furthest ring a drone can *reach*, the furthest it can *hold*, and the swarm size beyond which coverage stops growing.

The reach ceiling $k_{\max}$. A drone leaves the base with full charge B and pays c_{move} per cell travelled outward. Under the proportional threshold it must always keep enough charge to fly straight home, i.e. it turns back at ring k once $b_i \le kc_{\text{move}}$. To *arrive at* ring k (having spent kc_{move}) and *still* be able to return (needing another kc_{move}), it must satisfy $B - kc_{\text{move}} \ge kc_{\text{move}}$ hence:

Proposition 1 (Reach ceiling)**.** *Under the return-distance-proportional threshold, the furthest ring a drone can settle on is* $k_{\max} = \lfloor B/(2c_{\text{move}}) \rfloor$. *Under a fixed reserve* r *the one-way constraint* $B - kc_{\text{move}} \ge r$ *gives* $k_{\max} = \lfloor (B-r)/c_{\text{move}} \rfloor$.

Remark. $k_{\max}$ depends only on a *single drone's* budget B and cost c_{move} and contains no N: however many drones one owns, none settles past ring $k_{\max}$. Only the per-cell cost c_{move} enters, however that cost is composed, so the ceiling is robust to the details of the energy model. The factor 2 is the round trip, so the ceiling is tied to the *single-base, mandatory-return* regime: a sacrificial drone that lands for good reaches $\sim B/c_{\text{move}}$, twice as far but once. Section VI treats the relaxations.

The sustainable frontier: reach *vs* hold. Reaching a ring and *holding* it are different. A drone that arrives at ring k has spent kc_{move} and, keeping kc_{move} in reserve, can hover only $H(k) = (B - 2kc_{\text{move}})/c_{\text{hover}}$ rounds before it must turn back. That budget is thinnest at the ceiling, and vanishes there whenever $2c_{\text{move}}$ divides B, as it does at our defaults: ring $k_{\max}$ is then *touchable but not holdable*, since a drone reaching it must turn round at once and cannot be occupied in steady state. The frontier the swarm can actually keep filled is the largest holdable ring,

$$k_{\text{sus}} = \max\{k : H(k) > 0\} = \left\lceil \frac{B}{2c_{\text{move}}} \right\rceil - 1, \qquad (1)$$

at most one ring inside $k_{\max}$ (for $B = 20$, $c_{\text{move}} = 1$: $k_{\max} = 10$, $k_{\text{sus}} = 9$). This is why the measured reach saturates *at* the sustainable frontier rather than at the ceiling: the swarm converges on the sustainable disc of radius k_{sus}, only *approaching* ring $k_{\max}$ and never settling on it (Section V).

Duty cycle and the saturation swarm size. A drone holding ring k follows the cycle of Section III: out (k), hover (H), back (k), recharge (τ). Its budget obeys $2kc_{\text{move}} + Hc_{\text{hover}} = B$, so the on-station time is $H = (B - 2kc_{\text{move}})/c_{\text{hover}}$ and the fraction of the cycle it spends covering is

$$\rho(k) = \frac{k + H}{2k + H + \tau}. \qquad (2)$$

Recharging with no delay is the case $\tau = 0$. Because $\rho(k) < 1$, keeping one cell covered takes more than one drone. Each ring has its own duty fraction: inner rings recycle fast, since the trip is short and $\rho \to 1$, and outer rings slowly. Summing each ring's own requirement over the *sustainable* disc gives the *saturation swarm size*

$$N^\star \;\approx\; \frac{1}{\rho(0)} + \sum_{k=1}^{k_{\text{sus}}} \frac{6k}{\rho(k)}. \qquad (3)$$

Weighting each ring by its own duty fraction is what makes this sharp. The crude alternative applies the worst duty fraction, that of the outer ring, to the whole disc: $N_{k_{\max}}/\rho(k_{\max})$, writing $N_k = 1 + 3k(k{+}1)$ for the cells of the radius-k disc. At our defaults it predicts ≈ 993 drones against $N^\star \approx 316$ here, three times too many.

Below $N^\star$ coverage grows with N. At and above it, coverage plateaus and extra drones only thicken inner rings or cycle between the base and exhaustion. A longer recharge τ leaves the geometry alone, $k_{\max}$ and k_{sus} both, but lowers every $\rho(k)$ and so raises $N^\star$: the sustainable swarm thins. Section V overlays $N^\star$ on the measured plateau (Fig. 2).

V. Experiments

Setup. Every result comes from the simulator of Section III, run over 250 rounds with 10 seeds per point; means are reported with 95% confidence intervals and taken over the second half of the run, so that each figure describes the settled swarm rather than the expansion. Throughout, $B = 20$, $c_{\text{move}} = 1$, $c_{\text{hover}} = 0.05$, with the proportional return threshold and full recharge at $\tau = 10$. The ceiling study sweeps the swarm size; the study of unequal batteries fixes it at $N = 1200$, past the saturation size, so that the battery and not the swarm size is what limits the spread. Only drones in the field are counted, and quantities are averaged over rounds rather than read at the last one: drones leave to recharge in waves that repeat with the rounds, so a single final reading samples every seed at the same point of the wave. No comparison against a competing deployment algorithm is reported: the object of study is a *limit* rather than a method, and a limit admits no competitor. What we compare is the prediction against the measurement.

More drones cannot lift the ceiling. Fig. 2 plots the covered area as the swarm grows from 10 drones to 1600. From 250 to 1600, a factor of 6.4, it grows only from 193 to 260 cells, a factor 1.35. Over the same runs the ring reached moves from 8.85 to 9.15: it comes close to $k_{\max} = 10$ and never settles there, as Section IV predicts. The covered area per drone falls outright, from 0.77 cells at $N = 250$ to 0.16 at $N = 1600$: past the ceiling a new drone lands on a covered cell or never arrives. The predicted $N^\star \approx 316$ (Eq. 3) falls on the bend of the curve: the theory does not merely say that adding drones stops helping, it says at *which* swarm size.

Robustness of the ceiling. The measured reach follows the same $k_{\max} = 10$ under the *proportional* and *max* thresholds and under a safe *fixed* reserve, with no drone ever lost. An *unsafe* fixed reserve is the cautionary case: its one-way formula

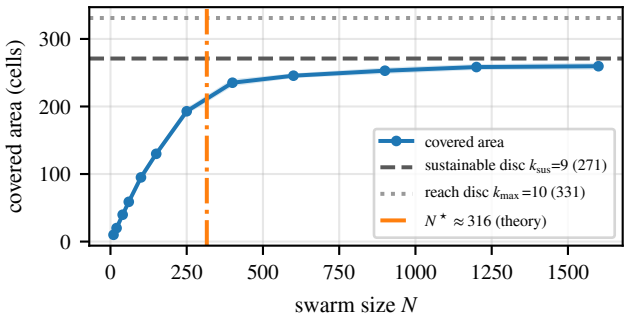


Fig. 2: The energy ceiling (10 seeds, 95% CI). The covered area levels off as drones are added, just short of the sustainable disc of radius $k_{\text{sus}} = 9$ and well short of the reach disc of radius $k_{\max} = 10$; the predicted $N^\star \approx 316$ falls on the bend.

promises $k_{\max} = 18$, but a drone that far out cannot pay for the return trip, and 66% of the swarm is stranded for no additional reach. Halving the refill per cycle acts as a halved B, the reach falling to 4.99 against a predicted 5. A longer recharge τ leaves $k_{\max}$ and k_{sus} unchanged while thinning the swarm, at the rate Eq. (2) predicts, and the thinning is an *edge* effect: rings 0 to 4 hold 99.3% or above and the core is solid, and it is at ring 8 that occupancy gives way, falling to 54.5%.

When batteries are unequal. Batteries age at different rates, so drone i carries its own charge B_i and has its own ceiling $k_{\max,i} = \lfloor B_i/(2c_{\text{move}}) \rfloor$. We keep the total capacity $\sum_i B_i$ constant and change only how unevenly it is shared, so that what differs between two swarms is the shape of the sharing and nothing else. Four shapes are compared throughout, drawn in Fig. 3: *equal*, every drone at the mean; *even*, capacities drawn uniformly about it; *split*, half large and half small; and *long-tailed*, a few much larger than the rest.

Proposition 2 (How far unequal batteries can reach)**.** *Ask each of the rings $1, \dots, K$ for one drone able to hold it, that is, one whose own ceiling $k_{\max,i}$ is at least that ring's index. By Hall's theorem [11] such a choice exists if and only if, writing the ceilings in decreasing order $d_1 \geq d_2 \geq \cdots$, we have $d_m \geq K - m + 1$ for every $m \leq K$. The largest such K is the* reachable frontier. *Whenever rings $1, \dots, K$ can be filled, giving the* largest *batteries to the* outermost *rings is best: it leaves the largest possible spare charge on the ring that has least, $\min_i(B_i - 2k_i c_{\text{move}})$ over the rings k_i it hands out, and that ring is the one that fails first. This asks for one drone per ring. It bounds how far the swarm can reach, and does* not *promise those rings are covered, which would take $6k$ drones on ring k.*

Fig. 3 is the result this paper is about. Past $N^\star$ adding drones buys nothing, as Fig. 2 shows; re-sharing the *same* total capacity among those *same* drones buys a great deal. The reach we measure rises from 9.14 for *equal* to 12.11 for *even*, 13.50 for *split* and 15.96 for *long-tailed*: an increase of 75% for no extra energy and no extra drone. The covered area

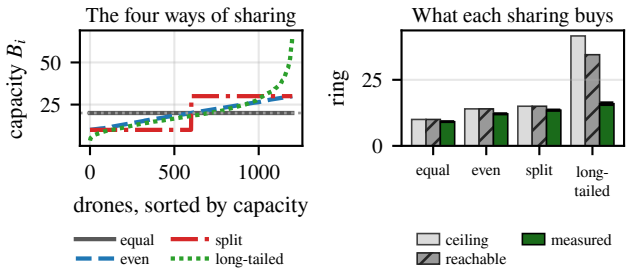


Fig. 3: The same total budget, shared four ways ($N = 1200$, past $N^\star$, 10 seeds, 95% CI). **Left:** the shapes themselves, each drone's capacity with the drones sorted; all four have the same mean, so the same area under the curve. **Right:** what each shape buys, in three bars per shape: the *ceiling* $\max_i k_{\max,i}$ that the largest battery could reach, the *reachable* frontier K of Prop. 2, and the reach we *measure*. The measured reach rises by 75% from *equal* to *long-tailed* without one extra drone or one extra unit of energy.

rises too, though not in step: 258 cells for *equal* against 463 for *split*, a gain of 79%, and 385 for *long-tailed*. The sharing of the battery, and not the swarm size, is what sets the spread.

The reachable frontier K of Prop. 2 rises with the shape as well, from 10 to 34.5, and comparing it against the measurement shows how much of it a battery-blind rule collects. For *even* and *split* it collects most: 12.11 of 14, and 13.50 of 15. It never reads a battery level: the rule builds the layered order of Prop. 2 on its own, the charge a drone carries and the ring it occupies correlating at 0.79 on the *split* swarm, because a drained drone stops moving and a fresh one passes it. For *long-tailed* it collects less than half, 15.96 of 34.5. The frontier asks for one drone per ring, whereas holding ring k asks for $6k$ of them. A long tail has a few very large batteries: enough to touch ring 34, far too few to stay there.

The gain also grows steadily with how uneven the sharing is. Sweeping the *split* sharing from equal to strongly uneven, at the same total budget, moves the measured reach from 9.14 to 15.20 and the covered area from 258 to 548 cells, rising at every step. Making the sharing more uneven costs nothing here: the innermost five rings stay filled, never below 99.5%, and connectivity never falls below 99.6%.

Concentrating the budget, on the other hand, costs a great deal, and Table I is the clearest statement in this paper that the ceiling is not the reach. Holding the gap between large and small fixed and giving the large batteries to ever fewer drones, the ceiling climbs to 105 rings while the measured reach *falls* to 7.9, below what an equal sharing attains, and the covered area collapses to 118 cells. Reach is best when about a third of the swarm carries the large batteries. A handful of enormous batteries buys a number on paper and loses the deployment.

Sensitivity to the one free parameter. The model has a single physically meaningful parameter, the ratio $c_{\text{hover}}/c_{\text{move}}$ of Section III, set to 0.05 above. Table II repeats the comparison across its plausible range, at the same $N = 1200$ and seeds.

TABLE I: Concentrating the same total budget on fewer drones ($N = 1200$, 10 seeds). The gap between large and small is held fixed, so the last row is the *split* sharing of Fig. 3. The ceiling is $\max_i k_{\max,i}$, what the largest battery could reach; the reach is what the swarm attains. They move in opposite directions.

large batteries	their B_i	ceiling	reach	area
5%	210	105	7.9	118
10%	110	55	10.2	176
20%	60	30	13.4	292
30%	43	21	**16.0**	409
50%	30	15	13.50	**463**

TABLE II: Measured reach against the hover-to-move ratio ($N = 1200$, 10 seeds), for the same total budget shared the four ways of Fig. 3. An unequal sharing wins at every ratio, and by more as holding a position grows dearer.

$c_{\text{hover}}/c_{\text{move}}$	equal	even	split	long-tailed
0.05	9.14	12.11	13.50	**15.96**
0.20	9.09	11.17	12.16	**13.75**
0.50	8.61	10.18	**10.85**	10.77
1.00	3.63	9.59	6.58	**9.92**

The ceilings do not move, since they do not contain the ratio. The measured reach does, and the equal sharing suffers by far the most: it loses 60% of its reach, against 21% for *even*. The advantage of an unequal sharing therefore holds at every ratio, and widens as the ratio grows, from $1.7\times$ at 0.05 to $2.7\times$ at 1.00. Which *unequal* shape wins does change, *split* falling behind *even* once holding a position is dear, for the reason given in Section III: a large battery pays for the trip out to a far ring, not for staying there. We claim no ordering among the unequal shapes.

VI. Discussion and limitations

Established results. The ceiling $k_{\max}$ (Prop. 1) is derived from first principles and confirmed in simulation: reach levels off at $k_{\text{sus}} = 9$, comes close to $k_{\max} = 10$ without settling there, and the predicted $N^\star$ falls on the bend of the area curve (Fig. 2). The sharing result is of a different kind: Prop. 2 bounds the distance a sharing makes *attainable*, but how much of it a battery-blind rule collects is measured, not derived.

Limitations. (i) The energy model is abstract. We work in budget units with $c_{\text{move}} = 1$ and $c_{\text{hover}} = 0.05$. The ceilings are geometry and do not depend on that ratio, but as Section III explains, which sharing of capacities reaches furthest does depend on it. Calibrating c_{move} and c_{hover} against a real rotary-wing model [3, 6], with a cost that varies with speed, is what would let us give $k_{\max}$ in metres and minutes, and it is needed before any absolute claim. *(ii) The result on unequal batteries needs the battery to be the binding constraint.* Below $N^\star$ the swarm is limited by its size instead, and the four sharings then differ by less than a single ring. The reachable frontier is geometry and stands either way, but the gain we report is a statement about a saturated swarm, which is also the only regime in which it is worth asking the question. *(iii) One base and a mandatory return is a modelling choice*, whose relaxations we listed in Section I and leave to future work. *(iv) Connectivity stays near* 100% *here* because the sustainable disc is dense; a thin-edge regime deserves its own study.

VII. Conclusion

Under a battery budget, how far a drone swarm spreads is set by the geometry of energy and not by how many drones there are. A drone can settle no further than $k_{\max} = \lfloor B/(2c_{\text{move}}) \rfloor$ and can hold only $k_{\text{sus}} = \lceil B/(2c_{\text{move}}) \rceil - 1$, so covered area and reach both level off; past $N^\star$ an extra drone only cycles between the base and exhaustion. We made that prediction quantitative and showed it survives every threshold and recharge variant.

What does set the reach is the subject of this paper: at a constant total budget it is the way capacity is shared out. Past $N^\star$, where an added drone buys nothing, sharing the same total capacity unevenly among the same drones raises the reach by up to 75% and the covered area by up to 79%. We derive the furthest ring such a sharing can reach, and a rule that never reads a battery level attains most of it on its own, because a drained drone stops and a fresh one passes it, so the swarm sorts itself by capacity. It falls short only under a long tail, where a handful of very large batteries can touch a far ring but are too few to hold it.

As Section VI sets out, the picture still awaits a calibration of the energy model against a real platform, which is also what would settle which sharing reaches furthest. Neither gap touches the claim: *under a battery budget, coverage is bounded by the geometry of energy and by how battery capacity is shared, not by the swarm size nor by the swarm's total capacity*.

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