UESTC4020: Wireless Sensor Networks

Report on Laboratory Sessions 1 & 2

Group Members:

Student Name:	GUID
谢乐天	2959471
何炳辰	2959544

Statement of Contribution:

谢乐天 (2959471): experiment logic and computational code design.

何炳辰 (2959544): plotting code design.

Introduction:

This laboratory investigates connectivity, radio-link requirements and minimum-hop routing in a wireless sensor network of 50 nodes distributed over a 1 km by 1 km area [1,2]. MATLAB R2024a was used to identify the collecting node, determine a sufficient communication radius, compare three carrier frequencies and evaluate routes to the collector. The minimum radius on the prescribed 5 m grid is 190 m. At this radius the mean minimum hop count is 4.428571, and the baseline Shannon capacity is 5.813602 Mbit/s. The results show how reducing hop count can require substantially greater transmit power.

Exercise 1: Identification of the sync node

The 50 coordinate pairs were loaded from labdata.txt in their original row order; the row number is the node identifier. The collecting node is called the sync in the laboratory sheet and is referred to as the sink below. The reference point was taken as (0,0), as explicitly specified in Exercise 1 [1]. For each node i, the distance to that point was calculated as di = sqrt(xi^2 + yi^2).

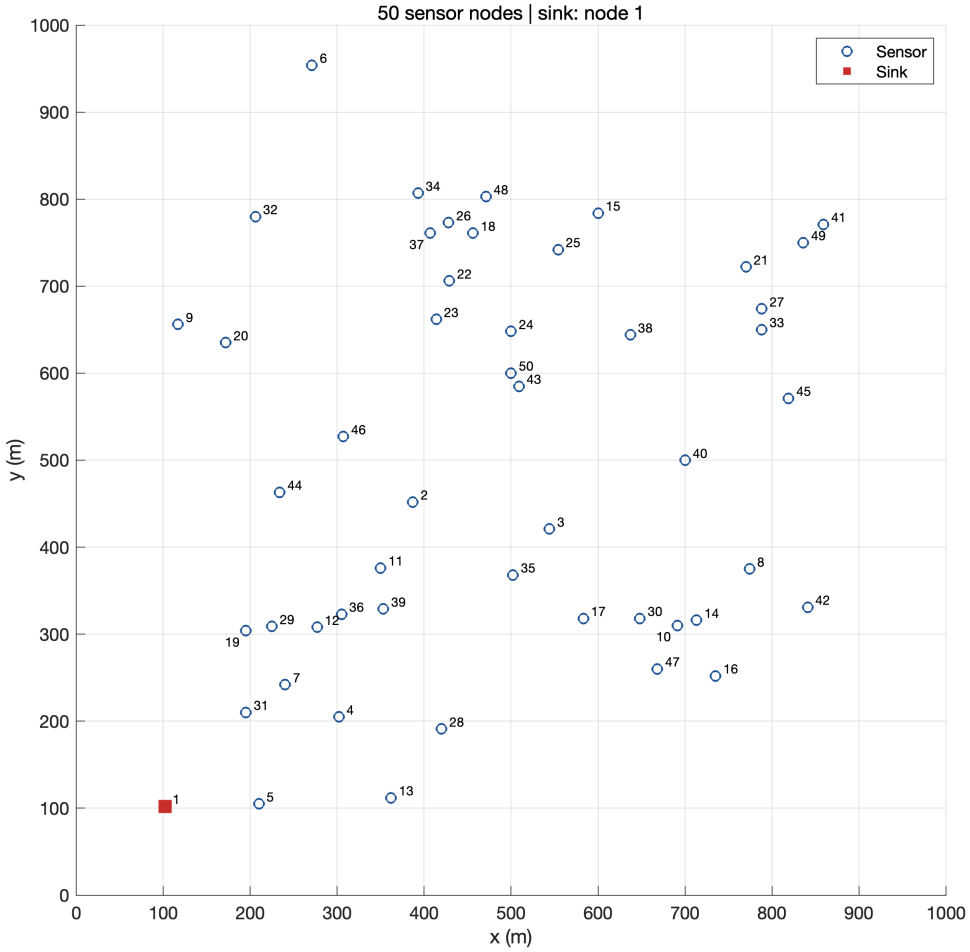


Figure 1. Sensor locations and identifiers; the red square marks sink node 1.

The minimum distance is 144.249783 m at node 1, whose coordinates are (102,102). This node is highlighted with a red square in Figure 1. The origin is used as the stated reference point rather than substituting the geometric centre (500,500), which would select a different node.

Exercise 2: Unit disk model

A pairwise Euclidean distance matrix was constructed, with Dij = sqrt((xi-xj)^2 + (yi-yj)^2). A link exists when i differs from j and Dij <= r. Diagonal distances were set to infinity so that a node cannot count itself as a neighbour. For each radius r = 10, 15, 20, ... m, nodes with zero neighbours were counted.

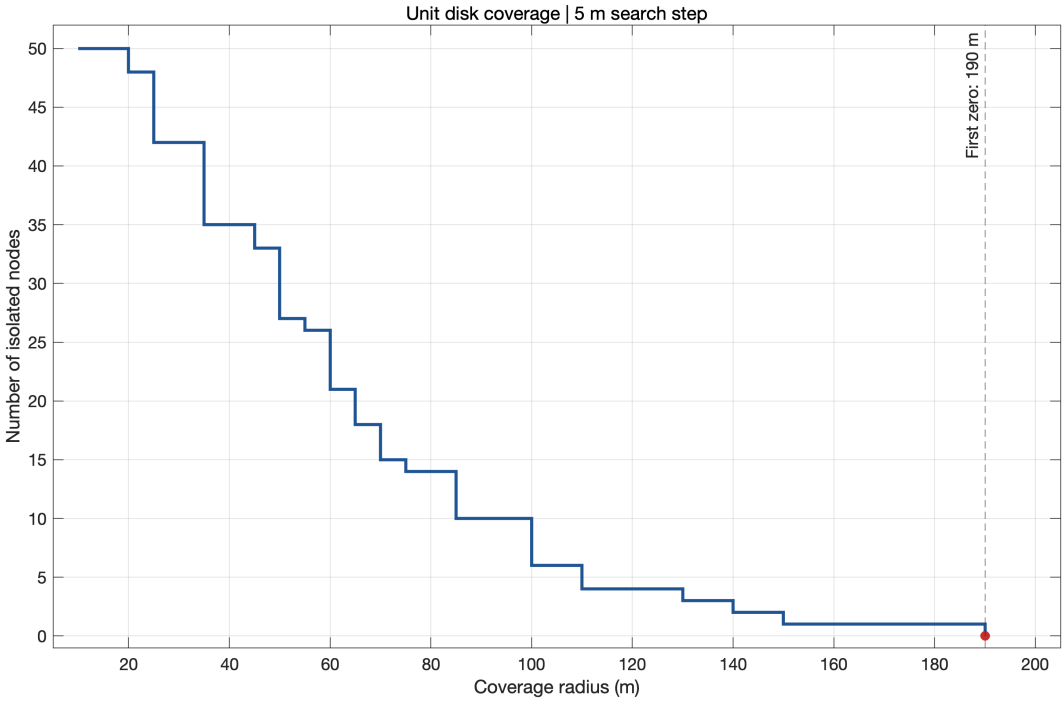


Figure 2. Number of isolated nodes as the unit disk radius increases in 5 m steps.

At both 10 m and 15 m, all 50 nodes are isolated. The count falls to 48 at 20 m, to one at 150 m, and remains one at 185 m. At 190 m it becomes zero for the first time. The exact continuous threshold is max_i min_(j != i) Dij = 185.744448 m; rounding up to the prescribed search grid gives r0 = 190 m.

Increasing the radius can only add links, so the isolated-node count is non-increasing. It falls in steps because links appear only when the radius crosses an inter-node distance. Having at least one neighbour does not by itself guarantee connectivity: separate groups can each have internal links. A separate reachability check confirms that all 50 nodes in this dataset are connected at 190 m, with 193 undirected links. A larger radius provides more routing choices, but maintaining the same boundary receive power requires more transmit power and may enlarge the interference region.

Exercise 3: Transmit power and data rate.

The free-space Friis model [1,3] was evaluated with unity transmit and receive gains. The link distance was set to d = r0 = 190 m, representing a boundary link of the network found in Exercise 2. The required receive power is Pr = -50 dBm = 10^-8 W. With c = 299792458 m/s and wavelength lambda = c/f, the required transmit power is:

Pr = Pt Gt Gr [lambda/(4 pi d)]^2
Pt = Pr [4 pi d f/c]^2, with Gt = Gr = 1.

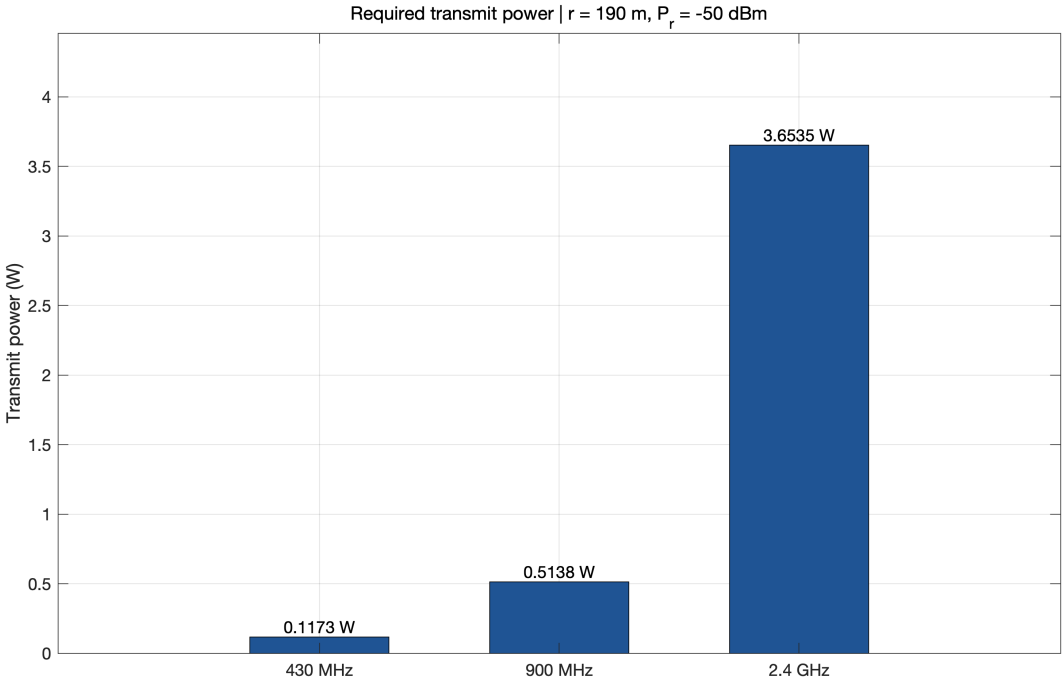


Figure 3. Transmit power required for -50 dBm reception over 190 m.

The required powers are 0.117280 W (20.6922 dBm) at 430 MHz, 0.513772 W (27.1077 dBm) at 900 MHz and 3.653491 W (35.6271 dBm) at 2.4 GHz. At fixed distance and antenna gains, required transmit power scales with f^2. The 2.4 GHz requirement is approximately 31.15 times the 430 MHz requirement. These are ideal free-space link-budget values; additional losses and hardware limitations are outside this model.

For the capacity calculation, the stated noise floor of -85 dB is interpreted as -85 dBm total noise power over the 500 kHz bandwidth. This gives N = 3.162278 x 10^-12 W. The receive SNR is 35 dB, or 3162.277660 in linear units. Shannon capacity for an additive white Gaussian noise channel is C = B log2(1 + SNR) [4]. Thus C = 500000 log2(1 + 3162.277660) = 5.813602 Mbit/s.

All three carrier frequencies give the same capacity because their transmit powers are individually chosen to provide the same received signal power, while bandwidth and noise power are unchanged. This is an ideal single-link capacity bound; it does not include protocol overhead, interference, retransmissions or multi-hop scheduling.

For a 10% increase, the target is Cnew = 1.1 C = 6.394962 Mbit/s. The required linear SNR is SNRnew = 2^(Cnew/B) - 1. At unchanged path gain and noise, Pt,new/Pt = SNRnew/SNR = 2.239184. Therefore the transmit-power increase is 123.918366%, equivalent to 3.500897 dB.

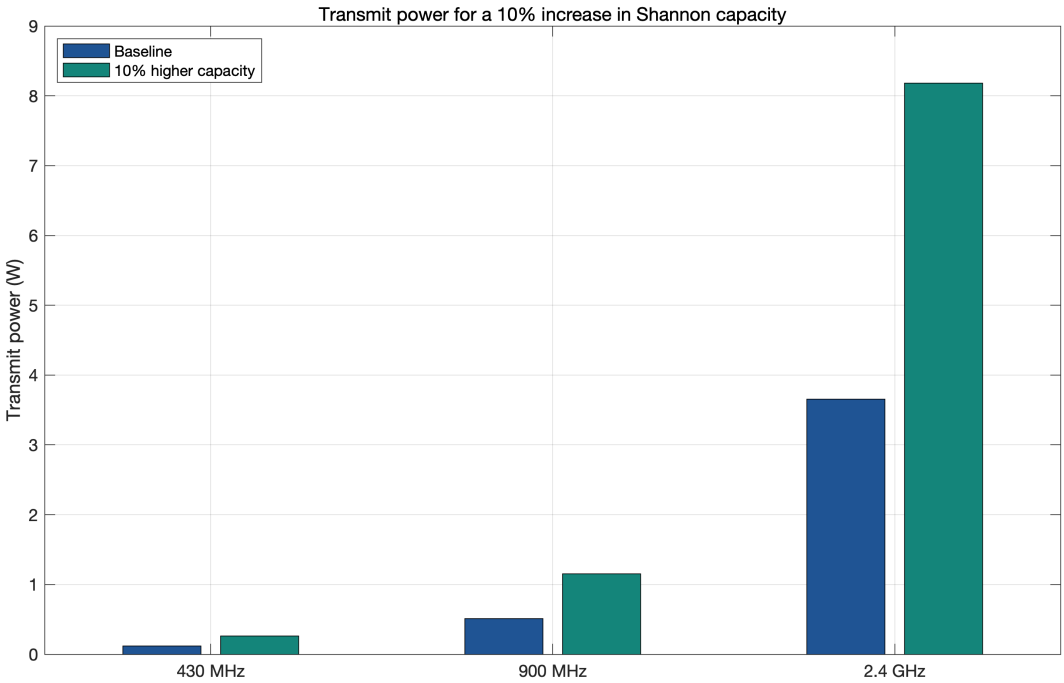


Figure 4. Baseline power and power required for a 10% increase in capacity.

The new powers are 0.262611 W (24.1931 dBm), 1.150430 W (30.6086 dBm) and 8.180837 W (39.1280 dBm) at 430 MHz, 900 MHz and 2.4 GHz, respectively. The absolute increases are 0.145331 W, 0.636658 W and 4.527346 W. The percentage increase is identical in all bands because the starting SNR is identical. A 10% rate increase requires much more than a 10% power increase because capacity grows logarithmically with SNR.

Exercise 4: Average minimum hop count

The network was represented as an undirected, unweighted graph: each sensor is a vertex and each permitted radio link has a cost of one hop. Breadth-first search (BFS) starts from the sink. All hop counts are initially infinity except the sink count of zero. A first-in, first-out queue stores discovered vertices. When an undiscovered neighbour v of vertex u is found, its hop count is set to h(v) = h(u) + 1, its parent is set to u, and it is appended to the queue. Neighbours are visited in ascending node-ID order, which gives reproducible choices between equally short routes.

BFS visits the graph by increasing hop distance, so the first discovery of a vertex yields its minimum hop count. Following parent pointers from a source back to the sink reconstructs a route. The reported mean is Hmean = sum_(i != sink) h(i)/49; the sink itself is excluded because its own route requires no transmission. Unreachable vertices retain an infinite distance and are checked explicitly rather than omitted from the average.

For an adjacency-list graph, BFS requires O(V + E) work. This implementation scans rows of a stored adjacency matrix, so its per-radius worst-case cost is O(V^2), with O(V^2) matrix storage. This is small for 50 nodes. The custom BFS results were checked against MATLAB graph distances with the unweighted method [5], and all 4200 node-radius hop values agreed across the 84 tested radii.

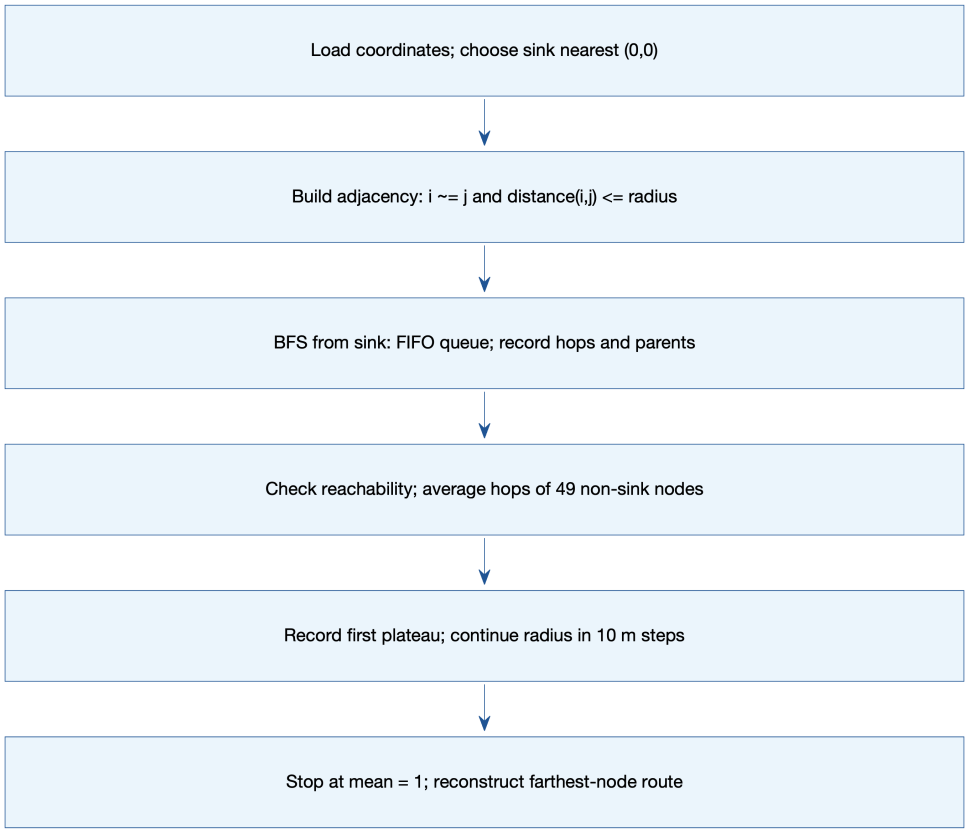


Figure 5. Analysis workflow, including the first-plateau record and the extended scan.

At r = 190 m, the 49 sources require 217 transmissions in total to deliver one packet each, giving a mean of 217/49 = 4.428571 hops. The largest minimum hop count is seven. Node 41 at (859,771) is the geographically farthest node from the sink, at 1010.252444 m. Its selected minimum-hop route is 41 -> 33 -> 40 -> 3 -> 2 -> 12 -> 31 -> 1.

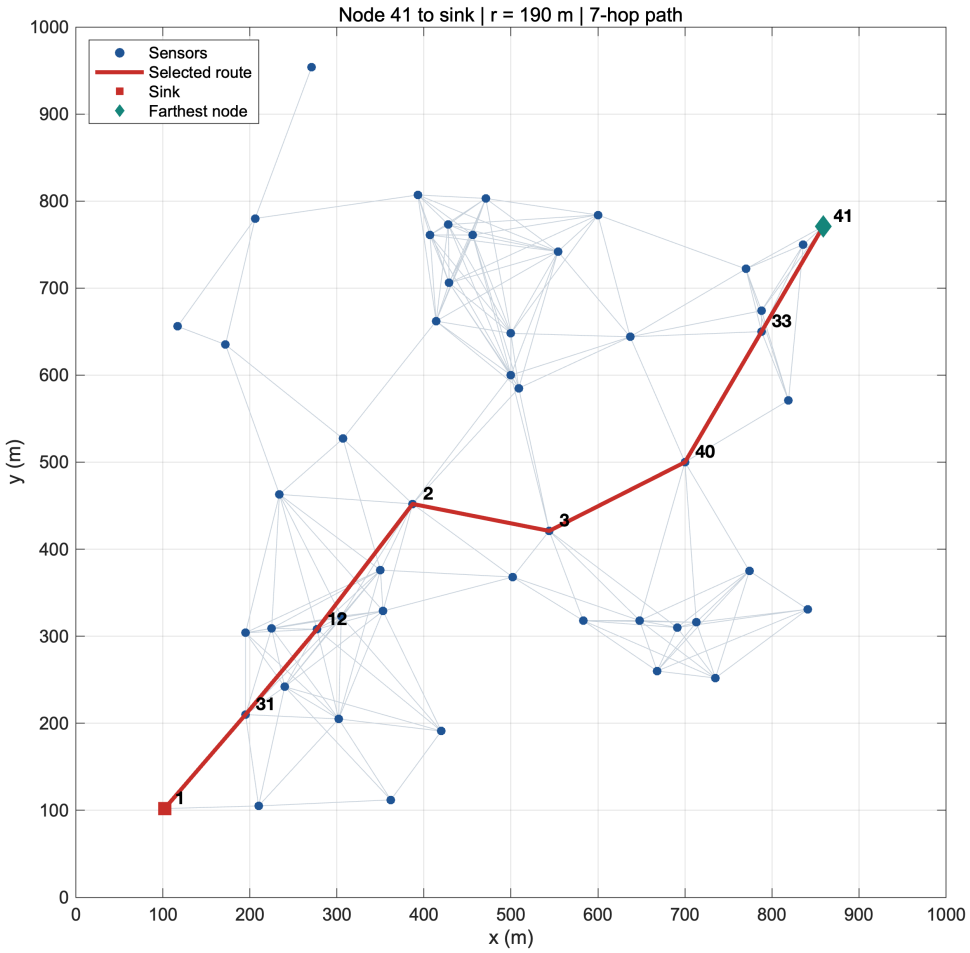


Figure 6. Seven-hop route from the farthest node to the sink at r = 190 m.

The seven link lengths are 140.293, 173.908, 174.863, 160.031, 181.207, 127.781 and 142.524 m. Each is within the 190 m limit. The route minimises hop count; it is not selected to minimise the sum of physical link lengths.

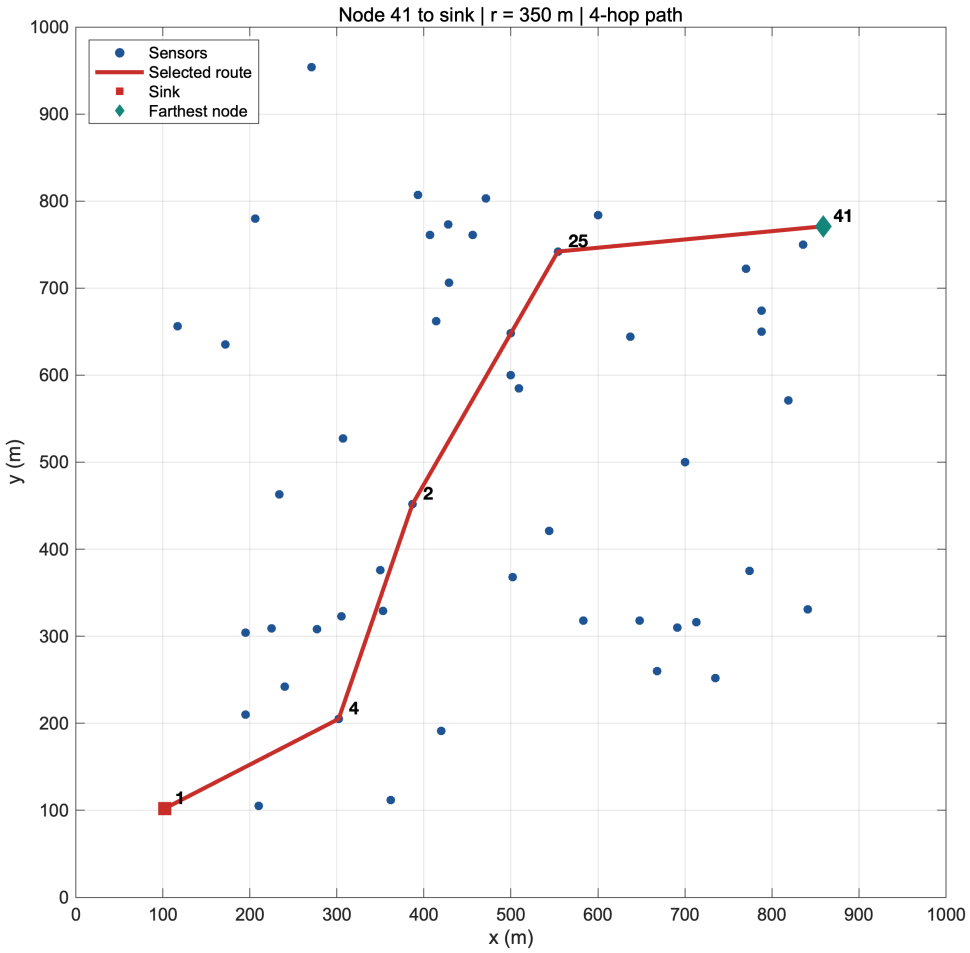


Figure 7. Four-hop route at the first plateau, r = 350 m; the same route is valid at 340 m.

At 350 m, the farthest-node route is 41 -> 25 -> 2 -> 4 -> 1, requiring four hops. Its link lengths are 306.376, 334.648, 261.216 and 224.964 m, so the same route is already feasible at 340 m.

The radius was increased from 190 m in 10 m steps. Under the literal rule of stopping at the first unchanged mean, the search stops at 350 m: both 340 m and 350 m give Hmean = 111/49 = 2.265306. The smallest radius achieving that mean within this initial scan is therefore 340 m. With the original 900 MHz transmit power fixed, a 340 m boundary link has Pr = -55.0545 dBm and C = 4.974569 Mbit/s; the corresponding values at the 350 m stopping point are -55.3063 dBm and 4.932792 Mbit/s.

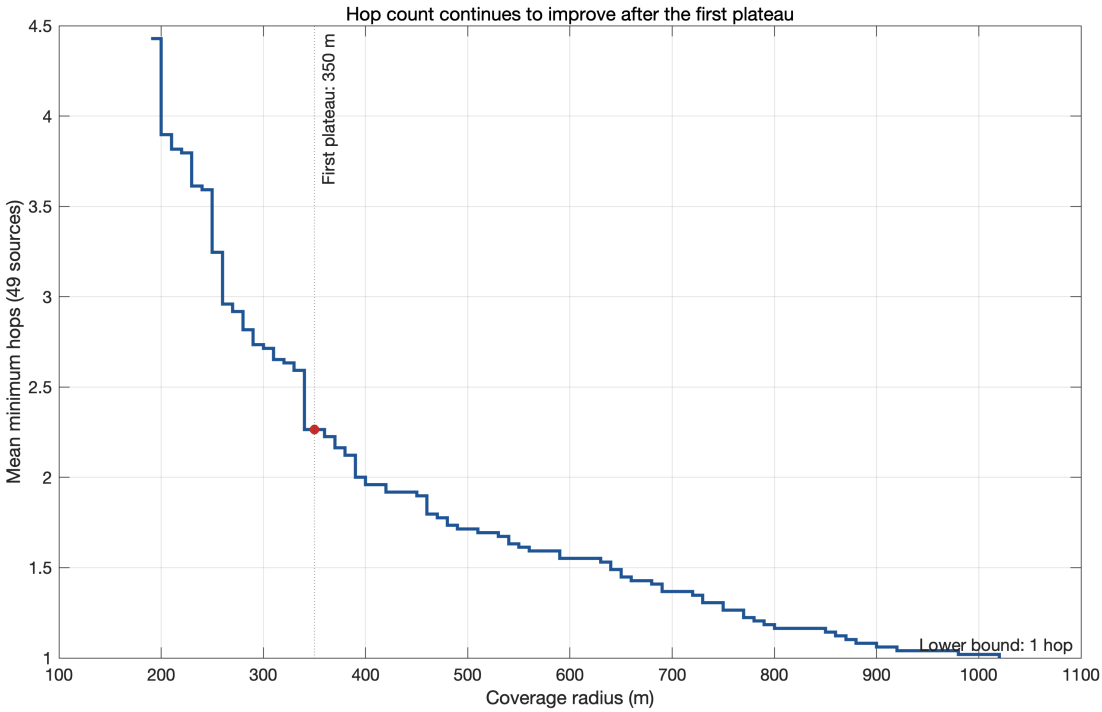


Figure 8. Mean minimum hop count versus radius; a temporary plateau occurs at 350 m.

An additional scan was retained to test whether the plateau is a true optimum. At 360 m the mean decreases again to 2.224490. It reaches 1.959184 at 400 m, and reaches the lower bound of one hop at 1020 m, where every source can transmit directly to the sink. The exact direct-connection threshold is 1010.252444 m; 1020 m is the first qualifying point on the prescribed 10 m grid. The 1020 m result is an extension, while 350 m remains the first-plateau stopping result requested by the local stopping rule.

For a consistent radio comparison, two cases were evaluated. First, keeping each frequency at its own 190 m baseline transmit power gives Pr(r) = -50 + 20 log10(190/r) dBm. Boundary receive power and capacity then decrease as r grows. At 1020 m they are -64.5969 dBm and 3.395421 Mbit/s. These longer links no longer satisfy the original -50 dBm target; this case shows the consequence of relaxing that target.

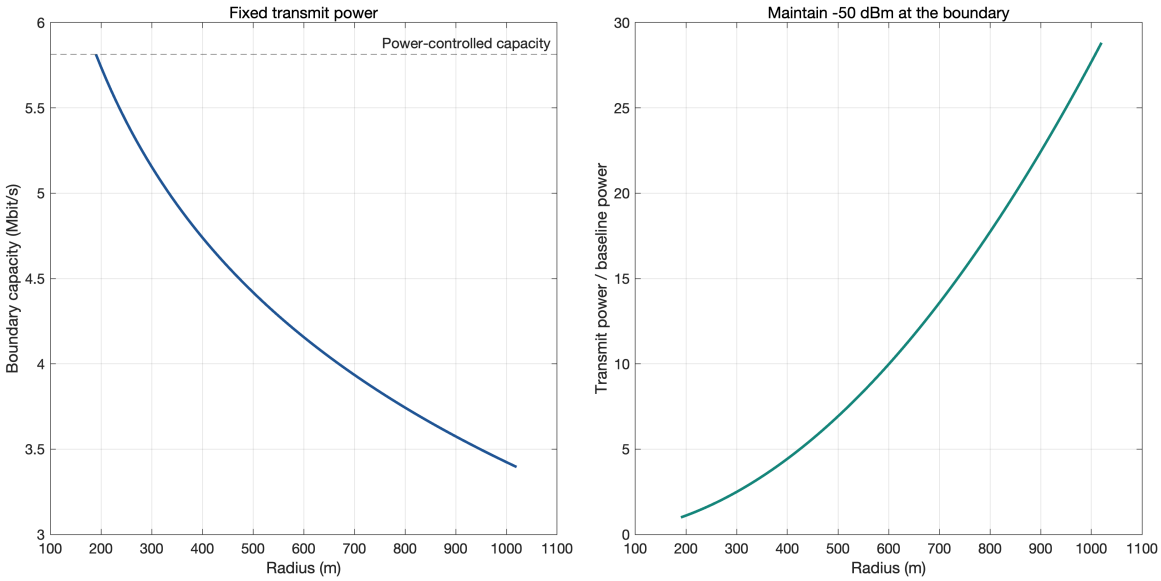


Figure 9. Fixed-power boundary capacity and the power multiplier needed to maintain -50 dBm.

Second, maintaining the -50 dBm boundary target requires Pt(r) = Pt(190) (r/190)^2. Capacity then remains 5.813602 Mbit/s at all three individually calibrated frequencies. At 900 MHz the required powers are 0.513772 W at 190 m, 1.645209 W at 340 m, 1.743410 W at 350 m, 2.277106 W at 400 m and 14.806884 W at 1020 m. The final radius therefore needs 28.819945 times the baseline transmit power. At that radius, the 430 MHz and 2.4 GHz powers are 3.379991 W and 105.293400 W. No transmitter-power limit is imposed in this mathematical scan.

The BFS solution guarantees minimum hop count and is straightforward to implement and verify. Fewer hops reduce the number of forwarding transmissions and can reduce forwarding delay under a comparable schedule. However, increasing range does not by itself minimise energy or guarantee a higher end-to-end data rate. Its larger power requirement must be balanced against fewer transmissions, and simultaneous transmissions can produce interference and contention that are absent from the unit disk model.

The deterministic parent choices can concentrate load on a few relays. With one packet per source per round and no aggregation, node 31 forwards 30 other-source packets at 190 m. At 340 m and 350 m, node 4 forwards 25. At 1020 m no relay is needed, although the sink must still receive the traffic of 49 sources. Choosing among equal-hop paths using residual battery energy or current relay load could distribute work more evenly; such balancing is not included in this implementation.

A supplementary radiated-energy estimate illustrates the trade-off. With 1000-bit packets, a common link rate of 5.813602 Mbit/s, and uniform 900 MHz transmit power set for each radius, Erad = Pt x total transmissions x 1000/C. The estimates per collection round are 19.1772 mJ at 190 m, 31.4122 mJ at 340 m, 33.2872 mJ at 350 m, 37.6019 mJ at 400 m and 124.8000 mJ at 1020 m. Thus fewer hops do not reduce this particular energy estimate. These values exclude receiver energy, electronic circuitry, idle listening, packet losses and retries; they are not a battery-lifetime prediction.

Conclusion:

The specified origin selects node 1 as the sink, and 190 m is the smallest 5 m-grid radius that eliminates isolated nodes; the network is also connected at this radius. Maintaining -50 dBm reception over 190 m requires increasing transmit power as carrier frequency increases, while equal bandwidth, received power and noise give the same 5.813602 Mbit/s capacity in all three bands. Raising capacity by 10% requires a 123.918366% transmit-power increase.

BFS gives a mean minimum hop count of 4.428571 at 190 m and a seven-hop route for the farthest node. The first plateau is detected at 350 m, with the same mean of 2.265306 already achieved at 340 m. Continued scanning reaches one hop per source at 1020 m. The results distinguish minimum-hop routing from energy-efficient or load-balanced routing: greater range reduces hop count but can substantially increase power demand, while the bitrate outcome depends on whether transmit power is fixed or adjusted.

References:

[1] UESTC4020, Wireless Sensor Networks: Laboratory Sessions 1 & 2, laboratory handout, release 15 September 2025.

[2] UESTC4020 laboratory dataset, 50 sensor coordinate pairs supplied in the one-page file named pdf; node identifiers follow the original row order.

[3] The MathWorks, Inc., fspl: Free space path loss, MATLAB documentation. https://www.mathworks.com/help/comm/ref/fspl.html (accessed 24 September 2026).

[4] C. E. Shannon, A Mathematical Theory of Communication, Bell System Technical Journal, vol. 27, pp. 379-423 and 623-656, 1948, Theorem 17. https://people.math.harvard.edu/~ctm/home/text/others/shannon/entropy/entropy.pdf

[5] The MathWorks, Inc., distances: Shortest path distances of all node pairs, MATLAB documentation. https://www.mathworks.com/help/matlab/ref/graph.distances.html (accessed 24 September 2026).

Appendix:

The MATLAB source files are supplied as separate files in the same folder as this report: run_all.m, run_lab.m, bfs_min_hops.m, make_figures.m and labdata.txt. Run run_all.m in MATLAB to reproduce all calculations, validation and figures.