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Constrained Optimal Routing in Wireless Sensor Networks with Uncertain Network Connectivity

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Abstract

Wireless sensor networks (WSNs) work under stringent energy constraints as the nodes are generally battery-powered which may deploy in locations in which the replacement of the battery is difficult. The routing decisions does not only influence transmission energy but also dissipate energy at intermediate nodes and forward packets during multihop communication. Nevertheless, receiver energy can be an unavoidable component of multihop communication, which is frequently treated as implicit in energy-aware routing models. Additionally, practical WSNs experience uncertain wireless connectivity due to interference, obstruction, environmental conditions, fading, and node mobility. These factors make deterministic routing assumptions insufficient towards applications requiring reliable data delivery. Goal programming (GP) is used for a receiver-energy-aware constrained multi-hop routing framework under uncertain connectivity. The receiver-energy dissipation, total communication energy, residual-energy preservation, and route reliability are considered simultaneously. The route availability is integrated towards optimization along a logarithmic transformation, and the link availability is depicted probabilistically. The competing routing objectives are managed according to the predefined aspiration priority levels and aspiration levels. The excessive multihop forwarding, overuse of energy-constrained relay nodes and unreliable links are addressed through the formulation. The additional hops decrease the distance-dependent transmission expenditure, but the electronic energy and cumulative receiver energy are increased. Likewise, the required route reliability limits the feasible routing alternatives and increases the energy expenditure. Therefore, the framework proposes a flexible mathematical basis along network lifetime considerations, receiver-energy consumption, connectivity reliability and balanced energy efficiency under uncertain WSN environments.

Keywords: Wireless sensor networks; multihop routing; receiver energy; uncertain connectivity; route reliability; Goal Programming; energy-aware routing; constrained optimization.

1. Introduction

Wireless sensor networks (WSNs) comprise energy-constrained nodes collects and forward data to a sink. Replacement of battery becomes difficult, as energy-efficient routing becomes essential towards extending lifetime (Akyildiz *et al.*, 2002; Al-Karaki & Kamal, 2004). The multihop routing leads to the reduction of transmission energy using shorter links; however, each intermediate node receives and retransmits the packets. Subsequently, a route with low transmission energy will impose a significant energy burden. Wireless sensor networks (WSNs) comprise energy-constrained sensor nodes which is collected and forward data to the sink. As the replacement of battery becomes difficult, energy-efficient routing is essential in extending the network lifetime (Akyildiz *et al.*, 2002; Al-Karaki & Kamal, 2004). Multihop routing suppresses the transmission energy

through shorter links; however, each intermediate node must receive and retransmit the packets. Subsequently, a route consisting of transmission energy impose a significant receiver-energy burden.

The transmission cost, residual energy or hop count is focused through the convention energy-aware routing approaches (Heinzelman *et al.*, 2000; Chang &Tassiulas, 2004). Instead of treating the receiver energy as an independent routing consideration, it is included implicitly. Additionally, the obstacles, fading, interference and environmental changes affect the wireless links, which makes the connectivity uncertain. Therefore, the probabilistic link availability allows a more realistic representation of route reliability (Chen *et al.*, 2021).

These factors generate competing routing objectives: preserving node energy, reducing communication energy, limiting receiver energy and maintaining reliable connectivity. For such problems, Goal Programming (GP) provides several conflicting objectives which handledin accordance with their relative priorities (Jones &Tamiz, 2010; Gültekin *et al.*, 2023).

A receiver-energy-aware constrained multihop routing model is proposed with uncertain connectivity for WSNs. The total communication energy, residual node energy, receiver energy, and route reliability are considered by the model within the weighted goal programming framework.

2. Research Gap and Contributions

The existing WSN routing studies allow effective approaches for multihop communication and energy conservation; still, these three issues become important. Firstly, receiver energy is not treated as a separate routing objective. Secondly, uncertain link connectivity is not integrated into energy-aware route selection. Thirdly, a systematic multi-objective framework consists of residual node energy, energy consumption and reliability as the objectives.

These gaps are addressed in the proposed study through the following contributions:

1. Receiver-energy modelling: reception energy is explicitly involved in route evaluation.
2. Uncertain connectivity: each link is an available probability, and an end-to-end reliability requirement is imposed.
3. Goal Programming:the adjustable objective priorities incorporate receiver energy, total energy and reliability
4. Constraint-based routing: feasible routes should satisfy connectivity, reliability, and energy requirements.
5. Sensitivity analysis:various parameter levels and GP weight settings are used to examine how routing decisions change under varying network conditions.

The proposed paper provides novelty such as uncertain connectivity, residual node energy and uncertain connectivity in a priority-based multihop routing formulation.

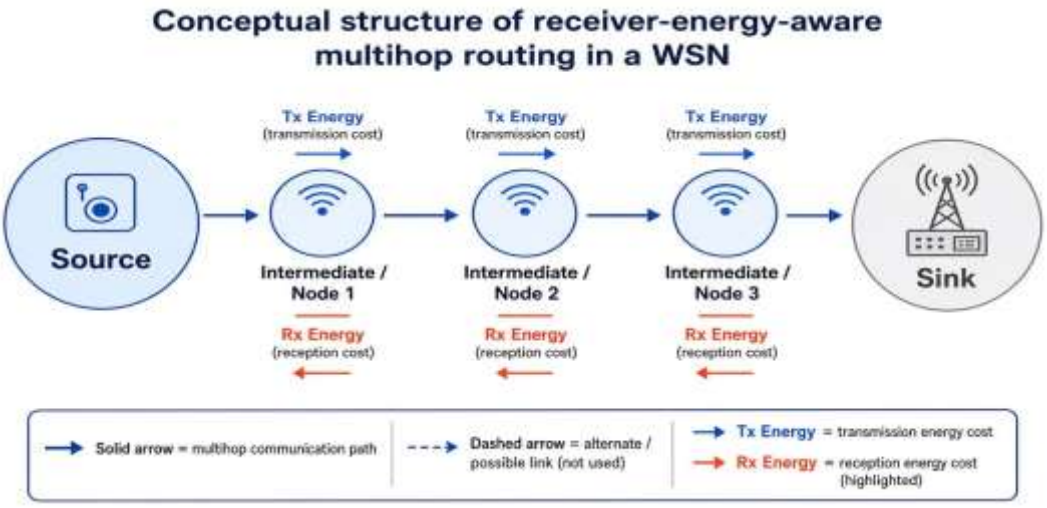


Figure 1. Conceptual structure of receiver-energy-aware multihop routing in a WSN.

Figure 1 summarizes the conceptual structure of the proposed routing problem, in which the source communicates with the sink using the intermediate sensor nodes. Simultaneously, the intermediate nodes incur transmission costs and reception costs, which illustrates that receiver energy becomes an essential component. The proposed formulation is distinguished from the conventional minimum-transmission-energy routing model

by the following features. Instead of treating node deletion, energy and reliability separately, they are incorporated into a single constrained multi-objective optimisation framework.

3. Network Model and Assumptions

3.1 Network Representation

The wireless sensor network is demonstrated as a directed graph.$G = (V, A)$, where V denotes the set of sensor nodes and Adenotes the set of feasible communication links. Each node has a limited initial battery energy along with its sensor and an arc.$(i, j) \in A$ shows the communication possibility from node i to node j. A source node s establishes the information packet, and a base station or a sink node b receives the final data.

The binary routing variable and each feasible communication link are associated. During the selection of the corresponding link as part of the source-to-sink route, if the variable is zero, the variable takes the value one. Subsequently, the selected route uses both the communication links and a sequence of intermediate forwarding nodes, which are determined through the optimization problem. The graph-based routing formulations, which are commonly used in WSN optimization maintains the consistency of the network representation (Al-Karaki & Kamal, 2004; Güney *et al.*, 2010). Moreover, this representation is extended through the present formulation in which the receiver energy and uncertain link availability are incorporated. Figure 1 illustrates the network structure conceptually. The source conveys information to an intermediate node, forwards and receives the packet. This process is repeated till the packet reaches the sink. Moreover, each intermediate node contributes to the completion of the route through both energy consumption and reliability characteristics.

3.2 Network Assumptions

To maintain a tractable mathematical formulation, we adopt the following assumptions.

1. Sensory nodes remain stationary during the routing decision period.
2. The source and sink nodes are predefined
3. Sensor nodes are equipped with limited initial battery capacity.
4. The Kbits of each generated packet remain fixed.
5. A candidate communication link is only considered if the two nodes involved are within the specified communication range.
6. The availability probability and distance are associated with each candidate link.
7. Historical observations, an appropriate wireless-channel model, or measurements are used to evaluate link availability probabilities.
8. The basic formulation assumes independent link availability events.
9. Each routing decision selects one source-to-sink route.
10. The basic model operates without considering data aggregation and packet compression
11. The energy required for reception is explicitly considered at forwarding nodes.
12. The chosen route needs to reach the required minimum reliability level.

These relationships among uncertain connectivity, receiver energy consumption and multi-hop routing are isolated towards those assumptions. The complex channel dependence, dynamic nodes, retransmission mechanisms, and data aggregation are incorporated in future extensions.

3.3 Routing Feasibility

A feasible route should provide a continuous connection between the sink and the source. When a node receives a packet as an intermediate relay, towards the next node on the route for outgoing communication. The intermediate node is prevented from inconsistent use by the routing formulation. The selection of the node is done without the corresponding forwarding connection mechanism. Likewise, the contribution of the links towards the source-to-sink path is eliminated during the selected route. The receiver-energy accounting is an important mechanism in the resulting structure, as each selected forwarding operation matches an actual reception event. Moreover, a significant part of the receiver-energy burden is determined by the route structure.

3.4 Node Energy Condition

The assumption of each sensor node has a finite initial energy budget. When the energy required from a participating node does not exceed its available energy, the routing solution becomes feasible. This condition plays an important role in the relay nodes. This condition is particularly important for relay nodes. A node can be placed in a spot and offer shorter ways to send messages, but using the same node over and over can use up

its battery power quickly. Therefore, the residual energy is considered through the proposed formulation because am additional routing concern instead of allowing route selection to depend on link distance. This approach creates a broader network-lifetime literature, which is consisitent an protectes nodes with limited residual energy are important in preventing premature network disconnections (Chang &Tassiulas, 2004; Dong *et al.*, 2016).

4. Communication Energy Model

4.1 Transmission and Reception Energy

The energy consumption depends on the electronic circuitry and the distance among communicating nodes. The first-order radio model is determined by Heinzelman *et al.* (2000), is broadly used in evaluating energy-efficient WSN communication.This modeltransmits a packet, which is required for an electronic energy, through the amplifier component, which is related to the communication distance, and receives the packet, that is required electronc energy towards the receiving nodes. The transmission and reception electronic costs are combined into a single per-link communication cost,

$$E_{ij} = K\left(2E_{\text{elec}} + \epsilon_{\text{amp}} d_{ij}^2\right) \qquad (1)$$

where $E_{ij}$is the combined communication energy associated with link (i, j), $E_{\text{elec}}$is the electronic energy required per bit, $\epsilon_{\text{amp}}$is the amplifier coefficient, and $d_{ij}$is the distance between nodes $i$and j.

Equation (1) is intentionally simple. The first term accounts for the electronic expenditure associated with transmitting and receiving the packet, while the second term represents the distance-dependent amplifier cost. The quadratic distance term is suitable for the free-space component of the commonly used first-order radio model (Heinzelman *et al.*, 2000).

4.2 Receiver-Energy Dissipation

Receiver energy is central to the proposed routing framework. The subsequent transmission becomes long or short as energy is consumed due to the packet being received through an intermediate sensor. The packet is forwarded to the subsequent node, as it incurs another communication cost. An important distinction is produced among the forwarding and transmission distance. A small amplifier expenditure uses short links, during the generation of considerable energy consumption as the packet is received repeatedly. Dense WSNs become an important issue. Many candidate intermediate nodes and,subsequently, possible multihop routes are often provided in dense networks. A route containing numerous short links is selected by the conventional distance-based routing model. Therefore, the proposed model treats receiver energy as a separate goal within the programming framework. This solution provides a distinction between the reduction in transmission distance and the actual reduction in the energy consumed through relay nodes.

4.3 Hop Count and Energy Trade-Off

The proposed formulation is not directly minimized through the number of hops. Rather, the interaction among the communication energy, residual node energy, reliability and receiver energy emerges. A direct source-to-sink link may involve a large length of transmission with the proportionally high cost of amplification. The use of relay nodes allows the transmission to be divided into a series of shorter links. Unfortunately, each relay introduced requires an extra reception and retransmission.So, more hops do not necessarily mean a monotonically decreasing overall energy consumption. There may be an energy saving to be gained by replacing one very long transmission with several shorter links in the beginning. However, when a suitable routing has been established, the additional costs of receivers and electronics might offset the savings from the reduced amplifier costs.

4.4 Residual Energy

The starting energy level alone of a node is not enough of a criterion as to whether that relay can be expected to be a stable one for long-term use. If routing decisions are based only on the proximity or on the energy costs for one immediate communication, a node that has less than average energy left in the battery could be used repeatedly.This issue is addressed through the proposed model, as it adds residual energy among the targets of the formulation of the Goal Programming. Is not necessary for the model to optimize for the greatest residual energy for each node individually, as this could create the problem unnecessarily harder. Rather, the model tries

to control the wear-out of the nodes that are more vulnerable.A connection between longer-term network sustainability and immediate routing cost is involved in the formulation. The residual energy is heavily used through the relays, which is preserved for future alternatives and reduces the likelihood of premature network partitioning.

5. Uncertain Connectivity and Route Reliability

5.1 Probabilistic Link Availability

The communication links are always not regraded through the permanent availability. The probability of successful communication is altered by fading, changing channel conditions, obstacles, hardware variability and interference. Subsequently, an availability probability p_{ij} is represented through the candidate link; higher values are indicated through the communication over the link is available.

Using probabilistic connectivity, the resulting model of uncertainty in wireless routing is more realistic than the assumption of explicit determinism of link availability. Recent research has focused specifically on the problem of route selection in WSNs under scenarios where uncertainty in connection failures is present, emphasizing the importance of considering link reliability in the search for energy-optimal routes (Chen *et al.*, 2021).

The probability p_{ij} are obtained through estimated or empirical measurements using the communication model. An example created through the historical packet-success observations is used for the estimation of the proportion of successful transmission in a particular link. Therefore, the probability estimates the updated network conditions changes.

5.2 End-to-End Route Reliability

The reliability of a multihop route and the reliability of its individual links are interdependent. The probability that is linked along the selected route remains available is obtained by multiplying the multiplication of corresponding link availability probabilities.

This presents an inherent challenge when it comes to multihop routing. While individual links may have relatively high availability, the overall availability of a path through a series of such untrusted links may be low because each link must be available for the entire path to get through. The proposed framework introduces a minimum route-reliability requirement. Let $R_{\min}$ represent the minimum acceptable route reliability. Instead of treating reliability as an output measure once after the route selection, the model is incorporated directly.

5.3 Logarithmic Transformation

The multiplicative nature of route reliability becomes complicated in the optimization process, as the reliability path is obtained from the selected link probabilities. The additive representation is obtained by taking the logarithm of route reliability. The multiplicative nature of route reliability can complicate optimisation because the resulting reliability condition is

$$\sum_{(i,j)\in A} x_{ij} \ln(p_{ij}) \geq \ln(R_{\min}) \qquad (2)$$

where x_{ij} indicates whether link (i,j) is selected and $R_{\min}$ is the required minimum route reliability.

Equation (2) provides a convenient mathematical representation because the logarithm converts the product of link probabilities into a sum. Since link probabilities lie between zero and one, their logarithms are non-positive. Therefore, the link with lower availability probabilities is selected to make the left-hand side smaller and cause the reliability requirement to be violated. Another important advantage of the log form relates to optimization. In certain cases, where the link probabilities are considered fixed parameters and the route variables are binary, the reliability requirement is able to be written as a linear constraint. This ensures the routing model that is obtained remains computationally tractable.

5.4 Reliability–Energy Trade-Off

There is a conflict between connectivity and energy efficiency. A highly reliable link allows the connected nodes to be at relatively large distances, but requires a high transmission energy to be spent, which is proportional to the distance. Conversely, a chain with a few short links will save on amplifiers, but will rely on many weak links, which lowers the overall reliability of the complete end-to-end connection.This interaction becomes one of the main reasons for adopting goal programming instead of a single-objective minimum-energy formulation.If the

minimum threshold for reliability is not very exacting, the process of optimization can select routes that optimize energy efficiency over a wider range of options. As the need for reliability becomes more exacting, some links that are not very likely can be discounted in terms of practically possible routes. Remaining routes could be more energy-intensive or could require relay nodes that are not used otherwise.

5.5 Role of Connectivity Uncertainty in the Proposed Model

With probabilistic connectivity, the routing problem effectively becomes an optimization problem with reliability constraints instead of a pure geometric one. Two routes that are roughly the same length can have various reliability profiles if they are made up of links with different probabilities of being available. This ability to discriminate becomes particularly interesting in terms of routing through receiver energy. A route which is made up of many short hops is generated in a large number of reception operations, while a different route with fewer links might require a much greater transmission distance. The need for reliability introduces another dimension to this balancing act.In accordance with the proposed framework, the evaluation of the routing alternatives is demonstrated using interconnected criteria: route reliability, residual node energy, communication energy, and receiver-energy dissipation. These criteria are used in the next section as the basis for the goal programming formulation.

6. Constrained Multihop Routing Formulation

The WSN is modelled as a directed graph.$G = (V, A)$, where denotes sensor nodes and A represents feasible communication links. A binary variable x_{ij}indicates whether link $(i, j)$is selected for the source-to-sink route. The routing constraints are ensured as the selected links form a continuous path from the source.s to the base station b.Flow-conservation constraints are introduced to ensure that the source node has an exit path, the sink node is on that path, and all intermediate nodes that facilitate routing have an ingress path and an egress path. Routing loops are removed from any routing paths, and thus a feasible source-to-sink routing path can be constructed. Similar graph-based integer programming formulations have also been used for WSN routing and network planning problems (Al-Karaki & Kamal, 2004; Güney *et al.*, 2010).Additionally, all the participating nodes have sufficient residual energy to support their communication; therefore, the optimization does not select routes that the current battery status cannot support. Also, the selected path should satisfy the minimum reliability constraint imposed by the model of uncertain connectivity.Hence, route feasibility is identified through the three conditions: minimum route reliability, path connectivity and node-energy availability. Within this feasible region, the goal programming demonstrates the routing solutions according to the specified objectives.

7. Receiver-Energy-Aware Routing

The consumed energy at the receiver is explicitly considered since each intermediate node must receive a packet before forwarding it. As a result, a multihop route with multiple links will generate more receptions than a route with fewer links.There is a trade-off between lowering energy spent on transmissions at the cost of the receiver. In the case of shorter links, we lower the distance-related energy cost for transmissions, but adding more hops increases the consumption of electronics and reception. Therefore, a route through decreasing energy consumption for transmission alone could be over-aggressive, with lots of forwarding operations.Energy at the receiver is also related to the residual energy of the node. If a relay is used repeatedly, its energy stock might be exhausted earlier and then later cause a bottleneck at the relay. Similarly, the work on energy-aware routing has mentioned how important the load of energy dissipation is to prolong the lifetime of the network (Chang &Tassiulas, 2004; Dong *et al.*, 2016).

8. Goal Programming Formulation

There are four major conflicting goals involved in the routing problem:

1. The total communication energy is decreased;
2. The receiver energy dissipation is reduced;
3. The high route reliability is maintained;
4. The residual energy at participating nodes is preserved.

An appropriate Goal Programming (GP) is obtained as these objectives are expressed along the aspiration levels and undesirable deviations (Jones & Tamiz, 2010). GP is applied towards the multi-objective WSN optimization problems, which involve energy and other network-performance measures (García-Pedrajas*et al.*, 2012; Gültekin *et al.*, 2023).

Letd_1^+ represents excess total energy, d_2^+excess receiver energy, d_3^-reliability shortfall, and d_4^-residual-energy shortfall. Equation 3 shows the weighted objective.

$$\min Z = w_1 d_1^+ + w_2 d_2^+ + w_3 d_3^- + w_4 d_4^-, \qquad (3)$$

where w_1, w_2, w_3, w_4represent the relative importance of the four goals.

The weights are bound to be nonnegative and normalized to sum to unity. An increase in the weight on receiver energy causes a greater focus on lowering the expenditure of reception. A greater weight on reliability increases the focus on maintaining reliable connectivity.

The solution derived this way presents a flexible compromise between energy efficiency, the energy usage by the receiver, reliability and remaining energy. Its sensitivity towards the relative weights of the objectives is therefore investigated through computational experiments.

9. Solution Procedure

The proposed method constructs a candidate network graph from node positions, link distances, available energy, and the predicted link availability probability; then, finding all possible paths from source to sink satisfying the flow, energy, and reliability constraints.

For each candidate route, transmission and reception energy are evaluated using the communication model. The four goal deviations are subsequently calculated relative to their aspiration levels. The weighted GP model is solved to determine the route having the minimum aggregate weighted deviation.

Subsequently, a sensitivity analysis is carried out through successive manipulation of parameters of the network and GP weights. Particularly, the receiver-energy, reliability and residual-energy weights are individually and collectively manipulated. This allows the research to assess various optimization criteria, which eventually lead to similar outcomes in terms of hop count, choice of relays, energy use and route reliability.

This becomes an important procedure as the proposed method does not intend to generate a unique universal optimal route. Rather, a priority-sensitive routing mechanism is provided for the selection of the route, which reflects the operating requirements of WSN.

10. Numerical Experiment Design

The experiments are designed to examine how the proposed receiver-energy-aware Goal Programming model fares when faced with the changing nature of the network environment and the relative importance placed on optimization. Rather than test the models with one particular setup, the experiments systematically change network size, node density, link reliability, communication distance, packet size, initial energy and the weights of the Goal Programming formulation. Thus, the experiments allow one to evaluate the proposed models under various routing conditions and, more importantly, reveal how the explicit inclusion of receiver energy affects the chosen multihop route. 100 × 100 m-square sensing field is considered. There are three main network sizes are used: 25, 50, and 100 sensor nodes, which relatively represent small, medium, and dense networks. The positions of the sink and source are opposite in the regions of the sensing field where multihop forwarding is required. Until otherwise stated, the initial energy of each sensor is set to **1 J**, the initial energy of each sensor is set to **1 J**, and the nominal communication distance is varied among 20, 40, and 60m.

10.1 Variation of Network and Communication Parameters

Network size is varied in the first experiment, where the sensing region is fixed. Increasing degrees of network density are sampled (representing increasing node levels of 25, 50, and 100). With 25 nodes, there are expected to be relatively few potential source-to-sink routes, and with 50 nodes there are additional forwarding choices; with 100 nodes there is a much denser routing scenario. It is hoped the model will be able to utilize these additional routes without undue expenditure of receiver energy.

The variations of the link-availability probability are varied at 0.70, 0.80, 0.90, and 0.95, which represent highly reliable communication conditions. The variation of the minimum end-to-end reliability requirement is separately obtained at 0.70, 0.80, 0.90, and 0.95. An important point to note is that a pathway with n boxes of medium reliability may have a smaller overall reliability than a pathway with a single high-reliability box. Therefore, our model should aim to compromise reliability and the energy used up by other routes. The assessment of communication distance is carried out at intervals of 20, 40, and 60 meters.

Table 1. Concrete Experimental Parameter Levels

Parameter	**Levels**	**Purpose**

Sensor nodes	25, 50, 100	Network-density effect
Link probability p_{ij}	0.70, 0.80, 0.90, 0.95	Connectivity uncertainty
Reliability target $R_{\min}$	0.70, 0.80, 0.90, 0.95	Reliability constraint
Communication distance	20, 40, 60 m	Hop/transmission trade-off
Packet size	1000, 2000, 4000, 8000 bits	Communication workload
Initial energy	0.5, 1.0, 2.0 J	Relay-energy availability

Table 1 represents the initial energy of sensors, which is considered to be 0.5, 1.0, and 2.0 J. When e0 is lower, the network would have to operate under energy budgets, but when e0 is higher, it would have the luxury of more options for relay selection. This argument is especially relevant for the residual-energy objective, as the same action could have a wide spectrum of results depending on the energy budget.

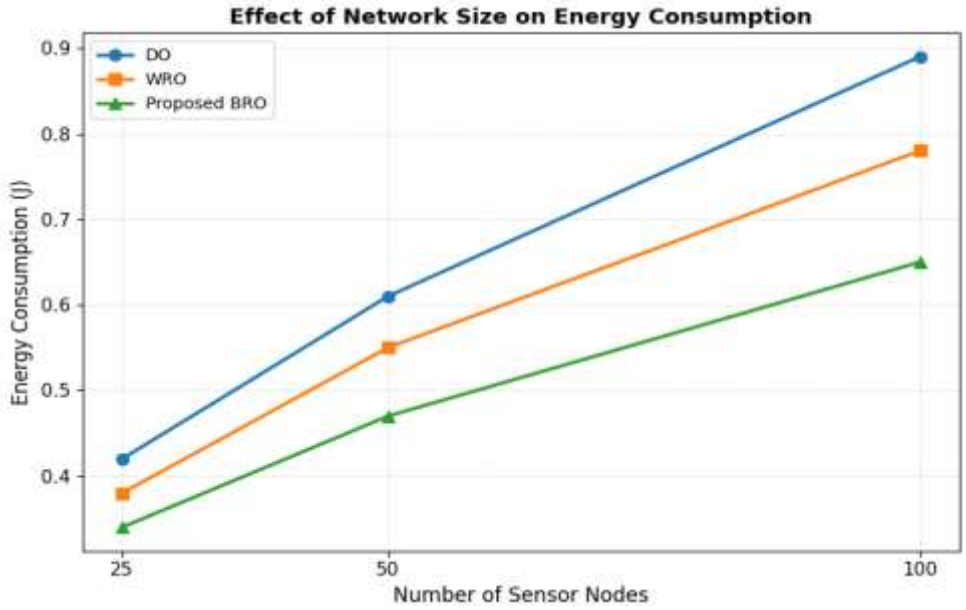


Fig. 2. Effect of network size on energy consumption for different optimization methods.

Figure 2 represents energy consumption against the number of sensor nodes: The trends of energy consumption with respect to the number of sensor nodes are plotted for the networks. As the network grows larger (from 25 to 100 nodes), it is observed that energy is normally very high as communication and routing overhead also increases, and the proposed BRO saves energy compared to DO and WRO.

10.2 Variation of Goal Programming Weights

The second group of experiments varies the Goal Programming priorities. A baseline case allows balanced weights, $w_1 = w_2 = w_3 = w_4 = 0.25$. The individual priorities are then raised to 0.50, whereas the remaining three weights are set to approximately 0.167 each. A stronger-priority case assigns 0.70 for the selected goal and approximately 0.10 to each of the remaining goals.

Table 2. Goal Programming Weight Scenarios

Scenario	w_1 **Energy**	w_2 **Receiver**	w_3 **Reliability**	w_4 **Residual energy**
Balanced	0.25	0.25	0.25	0.25
Energy-priority	0.50	0.167	0.167	0.167
Receiver-priority	0.167	0.50	0.167	0.167

Reliability-priority	0.167	0.167	0.50	0.167
Residual-energy-priority	0.167	0.167	0.167	0.50
Strong receiver priority	0.10	0.70	0.10	0.10
Strong reliability priority	0.10	0.10	0.70	0.10
Strong residual-energy priority	0.10	0.10	0.10	0.70

Table 2 represents a simple method to evaluate the novelty of the approach. When receiver energy is of higher priority, the model avoids unnecessary relays, even if an additional short link would reduce the overall communication distance. When reliability is of higher priority, routes with risky links should be discounted; when residual energy is of higher priority, the optimizer should avoid biasing forwarding activities in nodes with less remaining energy.

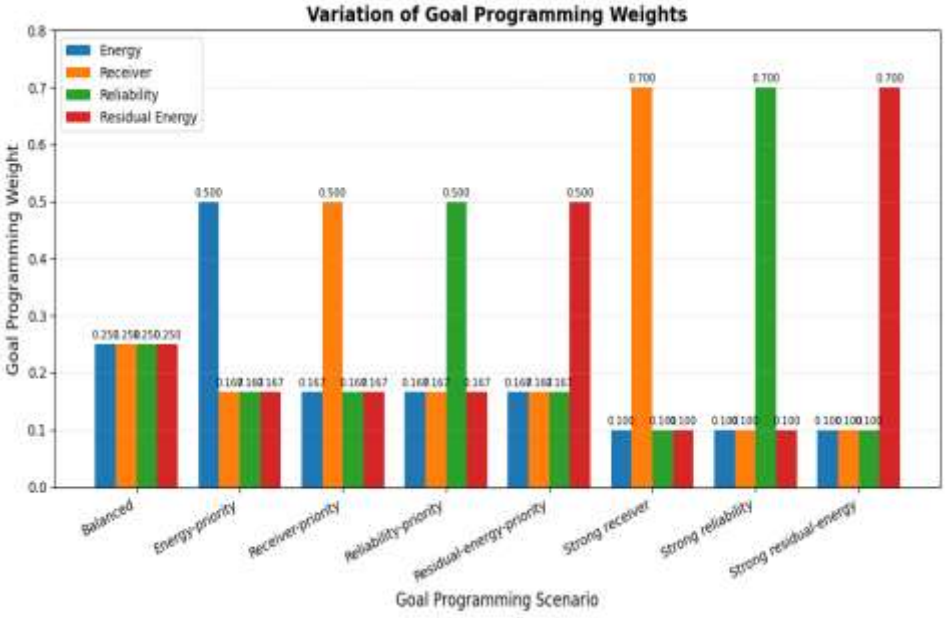


Fig. 3. Variation of Goal Programming weights under different priority scenarios

Figure 3 shows objective weights among the four objectives in the various Goal Programming cases. In the balanced case, all objectives have been assigned the same weight, and for priority cases, the weight assigned to the selected objective is highest, while the weights assigned to the remaining objectives are lowest. This highlights the flexibility of the model.

11. Conclusion

This paper proposed a receiver-energy-aware constrained multihop routing protocol for the connectivity-uncertain wireless sensor network based on Goal Programming. We have concurrently taken into account four relevant routing criteria, such as total communication energy, receiver energy, route reliability, and residual node energy. Differing from traditional approaches focusing on transmission energy or hop count minimization, the receiver energy has been modelled explicitly in our proposed routing method.

The experimental setup considered various network sizes, link success probability, quality of service, communication range, packet size, and initial node energy, all of which influence route availability and the trade-off between short transmission distance and increased reception cost at intermediate relays. Larger packet sizes and longer communication ranges increase the communication energy. More strict reliability constraints decrease the number of available routes.

The main value of this research is the integration of residual node energy, receiver energy, and probabilistic connectivity in a constrained GP model. This representation provides a systematic approach to balance the energy efficiency, reliability and node energy preservation requirements in multihop WSN routing. In this way, our

approach can serve as a generic mathematical model to guide routing decisions under an uncertain communication environment and energy sources.

References

1. Ahmad, A., Javaid, N., Ahmed, S. H., Bouk, S. H., Ilahi, M., & Kim, D. (2015). COME: Cost optimisation with multi-chaining for energy-efficient communication in wireless sensor networks. *International Journal of Ad Hoc and Ubiquitous Computing, 20*(3), 186–198. https://doi.org/10.1504/IJAHUC.2015.073172

2. Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., &Cayirci, E. (2002). Wireless sensor networks: A survey. *Computer Networks, 38*(4), 393–422. https://doi.org/10.1016/S1389-1286(01)00302-4

3. Al-Karaki, J. N., & Kamal, A. E. (2004). Routing techniques in wireless sensor networks: A survey. *IEEE Wireless Communications, 11*(6), 6–28. https://doi.org/10.1109/MWC.2004.1368893

4. Chang, J.-H., &Tassiulas, L. (2004). Maximum lifetime routing in wireless sensor networks. *IEEE/ACM Transactions on Networking, 12*(4), 609–619. https://doi.org/10.1109/TNET.2004.833122

5. García-Sánchez, A.-J., García-Sánchez, F., Rodenas-Herraiz, D., & García-Haro, J. (2012). On the optimization of wireless multimedia sensor networks: A goal programming approach. *Sensors, 12*(9), 12634–12660. https://doi.org/10.3390/s120912634

6. Güney, E., Aras, N., Altınel, İ. K., & Ersoy, C. (2010). Efficient integer programming formulations for optimum sink location and routing in heterogeneous wireless sensor networks. *Computer Networks, 54*(11), 1805–1822. https://doi.org/10.1016/j.comnet.2010.02.009

7. Gültekin, B., Nurcan-Atceken, D., Altın-Kayhan, A., Yıldız, H. U., & Tavlı, B. (2023). Exploring the tradeoff between energy dissipation, delay, and the number of backbones for broadcasting in wireless sensor networks through goal programming. *Ad Hoc Networks, 149*, 103223. https://doi.org/10.1016/j.adhoc.2023.103223

8. Heinzelman, W. R., Chandrakasan, A. P., & Balakrishnan, H. (2000). Energy-efficient communication protocol for wireless microsensor networks. In *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences* (pp. 10–19). IEEE. https://doi.org/10.1109/HICSS.2000.926982

9. Jones, D., & Tamiz, M. (2010). *Practical goal programming*. Springer. https://doi.org/10.1007/978-1-4419-5771-9

10. Lindsey, S., & Raghavendra, C. S. (2002). PEGASIS: Power-efficient gathering in sensor information systems. In *Proceedings of the IEEE Aerospace Conference* (Vol. 3, pp. 1125–1130). IEEE. https://doi.org/10.1109/AERO.2002.1035242

11. Liu, X. (2012). A survey on clustering routing protocols in wireless sensor networks. *Sensors, 12*(8), 11113–11153. https://doi.org/10.3390/s120811113

12. Lyu, J., Ren, Y., Abbas, Z., & Zhang, B. (2021). Reliable route selection for wireless sensor networks with connection failure uncertainties. *Sensors, 21*(21), 7254. https://doi.org/10.3390/s21217254

13. Miettinen, K. (1999). *Nonlinear multiobjective optimization*. Springer. https://doi.org/10.1007/978-1-4615-5563-6

14. Pantazis, N. A., Nikolidakis, S. A., &Vergados, D. D. (2013). Energy-efficient routing protocols in wireless sensor networks: A survey. *IEEE Communications Surveys & Tutorials, 15*(2), 551–591. https://doi.org/10.1109/SURV.2012.062612.00084

15. Sasaki, S., Miyaji, Y., & Uehara, H. (2017). Energy budget formulation in progress-based nearest forwarding routing policy for energy-efficient wireless sensor networks. *IEICE Transactions on Information and Systems, E100-D*(12), 2808–2817. https://doi.org/10.1587/transinf.2017PAP0010

16. Shah, R. C., &Rabaey, J. M. (2003). Energy-aware routing for low energy ad hoc sensor networks. In *Proceedings of the IEEE Wireless Communications and Networking Conference* (Vol. 1, pp. 350–355). IEEE. https://doi.org/10.1109/WCNC.2002.993520

17. Younis, O., & Fahmy, S. (2004). HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. *IEEE Transactions on Mobile Computing, 3*(4), 366–379. https://doi.org/10.1109/TMC.2004.41

18. Zhang, H., & Shen, H. (2010). Energy-efficient beaconless geographic routing in wireless sensor networks. *IEEE Transactions on Parallel and Distributed Systems, 21*(6), 881–896. https://doi.org/10.1109/TPDS.2009.98

19. Dong, Y., Wang, J., Shim, B., & Kim, D. I. (2016). DEARER: A distance-and-energy-aware routing with energy reservation for energy harvesting wireless sensor networks. *IEEE Journal on Selected Areas in Communications, 34*(12), 3798–3813. https://doi.org/10.1109/JSAC.2016.2621378

20. Eraghi, N. O., Nabavi, S. R., & Akbari Torkestani, J. (2021). WSN routing protocol using a multiobjective greedy approach. *Wireless Communications and Mobile Computing, 2021*, Article 6664669. https://doi.org/10.1155/2021/6664669