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Optimal sink placement in backbone assisted wireless sensor networks

I. Snigdh [a,*], D. Gosain [a], N. Gupta [b]

[a] Department of Computer Science and Engineering, Birla Institute of Technology, Ranchi, India
[b] Department of Electronics and Communication Engineering, Birla Institute of Technology, Ranchi, India

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Abstract This article proposes a scheme for selecting the best site for sink placement in WSN applications employing backbone assisted communications. By placing the sink at a specific position, energy scavenging and delay constraints can effectively be controlled. In contrast to the conventional scheme for base station placement at the geographical centre or random placement at the end of the region of interest, the proposed scheme places the base station at either the graph theoretical centre or centroid of the backbone connecting nodes in the region of interest. This strategy shows a considerable reduction in the total number of hops that each packet needs to travel to reach the sink. The proposed scheme is applied on all the families of graphs prevalent in backbone assisted sensor networks to confirm the performance consistency and improvement in network parameters of the communication backbone measured in terms of delay, the carried load and the total energy consumption, eventually affected by the average number of hops for the message to reach the sink.

1. Introduction

Wireless Sensor Network (WSN) is all pervasive in world. From home automation system to critical boiler monitoring, and from X-Box to military surveillance, they are ubiquitous. Recently, considerable amounts of research efforts have enabled the actual implementation and placement of sensor networks tailored to the unique requirements of certain sensing and monitoring applications as mentioned by [1].

Every WSN is constrained by low data rates, energy reservations, and usually a many to one communication pattern. Analysing the performance of such networks has been done with the help of Steiner trees [2], shortest path trees [3] or greedy heuristic [4] based trees. These topologies have been put to numerous routing protocols, and data aggregation methods to optimize energy, load, response time or simply network longevity. The choice of a tree based backbone for our research is attributed and influenced by the literary works available for performance optimality. Protocols such as HTECRP [5] claim to manage congestion and perform fairness

* Corresponding author.
E-mail address: itusnigdh@bitmesra.ac.in (I. Snigdh).

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on the network by assigning privileges to the traffic. ViTAMin [6] offers a hierarchical backbone tree algorithm for energy efficiency and sufficient network lifetime. While Localized area spanning tree (LAST) protocols for wireless short range sensor networks optimize the energy cost and the interference imposed by the structure [7,8], a BFS based tree rooted at the base station offers shortest path traversal for each data message which utilizes the sensor resources efficiently by employing a local repairing approach for the crashing nodes thereby increasing the lifetime [6] similar to CTP [9,10]. Moreover, tree based strategies reduce the burden of retransmissions and hence can be used for congestion management [5]. Thus, it can be believed that a tree structure is popular in wireless sensor network structure, for most applications having one sink and too many sender nodes which justify our choice for further analysis. However, these researches focus on measuring the communication flows either for one or for multiple static or mobile sinks without emphasizing whether the placement of a sink too plays a role in determining the aforementioned network statistics such as delay, load and energy consumption. While tree based networks have been considered, the placement of sink has been done either at the root or at the source [11]. Also, source based trees and sink based tree construction algorithms have been analysed and used to optimize congestion in WSNs [12].

In addition to congestion control mechanisms, energy efficiency in communication also depends upon the sink placement strategy. Energy consumption can be estimated for WSNs, comparatively for static and mobile sinks. However, literatures [13] consider the energy consumption on the basis of mobility path and duty cycling of the nodes. The energy consumption of the nodes primarily depends on the communication distance. One way to reduce the communication distance is to deploy multiple static sinks and to program each sensor to route data to the closest sink [14]. Since the nodes near the sink forward and process more data, they tend to deplete early. The solution to this problem is to partition the region of interest into sub-fields with static sinks [15]. However, the main problem in adopting multiple sinks is to decide where to deploy them in the monitored region, so that, the data relaying load is balanced among all the nodes. The other situation is deploying mobile sinks in addition to static sinks. In case of mobile sinks, the random sink movements do not guarantee that data have been collected from all the nodes [16]. Therefore, there is a need of multiple mobile sinks to improve data collection in an efficient way.

Sink location strategies include deterministic as well as random deployments. The placement of sinks has been chosen to be at the end points of the region of interest (ROI) or the edges of a ROI as in [17,18]. Researchers evaluate the network performance when the sink is placed at the midpoint of the edges of the ROI, the centre of the ROI or even at the centres of clusters in case of portioned ROIs. The load on the sink can be decreased by adapting the high energy nodes around the sink as the base stations. However, there is no focus on the delay. On the contrary, delay has been observed by using GA based approaches but without considering energy optimization [18]. Our article considers both energy conservation and reduction in delay by appropriate sink placements in the network already connected.

Experimental results show that the optimal sink placement can increase the node degree and greatly reduce the average hop counts, leading to a longer lifespan [19,20]. Experimental evaluation confirms that topology aware algorithms give remarkable lifetime improvement as compared to geo-aware algorithms and naive centre placement strategy [17,21,22]. While there are local search techniques [23] that aim to maximize the worst case delay and extend lifetime of a WSN, in practical scenarios, there may be obstacles or wireless range constraints that may not make the sink placements feasible.

Our article, therefore addresses the problem of convergecast communication for a tree based topology. We try to present a strategy that, while a tree based backbone is incorporated as the steady backbone for convergecast communications, the choice of the node would be the most appropriate to serve the purpose of the sink. We argue that the performance of the tree based communication is better if the sink is placed at the centroid or the graph theoretic centre of the tree.

We further divulge from comparing or proposing any best suited tree construction algorithm in terms of optimality. We further assume that the network employs a tree based backbone for carrying out the necessary data dissemination. These algorithms are employed at a separate computer and the sink relocation is performed either manually or by mobile sinks or robots. Our main aim is to isolate the minimum energy consuming node (MECN) that validates good performance in terms of the studied network parameters. We propose algorithms to identify the nodes appropriate to serve as the sink in a backbone assisted network on the basis of eccentricity and node degrees of the graphs.

The proposed strategy ensures that, irrespective of the backbone generation strategy employed for typical WSN applications, the optimal sink position falls at either the tree theoretic 'centre' or the 'centroid' of the graph. As the number of hop counts is basically determined by a routing scheme which decides the best route from a source to a destination, the proposed work focuses on identifying the node that would optimize the network parameters under the frequently adopted routing protocols for networks. Hence, our analysis is based on experimental results of default routing protocols for all families of trees to confirm our observations.

2. Preliminaries

Definition 1 (*Geographic Centre (GC) of Topology*). Assuming 'N' sensors placed in a field and represented as (x_i, y_i) coordinates in two dimensional plane, the 'GC(X, Y)' of any topology is calculated as $\mathrm{GC}(X, Y) = \sum x_i/n, \sum y_i/n$.

Definition 2 (*Tree Theoretic Centre (TTC) of Topology*). In order to define 'TTC' we first define distance in a tree '$T(V, E)$', as the distance '$d_T(V_i, V_j)$' between nodes 'V_i' and 'V_j' which is the minimum path length between them. In general, a centre is a vertex (or a minimum set of vertices) which minimizes some function involving the distance between an arbitrary vertex and the vertex in the centre.

- For $f(x) = \sum d_T(x, V),\ V \in V(T)$ where '$V(T)$' is set of all vertices in tree T; any vertex 'x' which minimizes $f(x)$ is known as the 'centre'. Alternatively, Centre can be viewed as min–max problem $\min\{\max d_T(x, V),\ V \in V(T)\}$.

- Eccentricity of vertex 'x' is defined as distance from 'x' to the vertex farthest from 'x' in '$V(T)$'. Thus, $E(x) = \max d_T(x, V)$, for $V \in V(T)$. Therefore, the vertex with minimum eccentricity is the 'centre' or 'TTC'.

Lemma 1. *Eccentricity of a vertex in a tree can be computed in linear time.*

Proof. Let T_x, denote the subtree rooted at vertex 'x' $\in V(T)$, which is the subgraph induced on vertex 'x' and all its descendants. Let *children*(x) denote the set of children of 'x'. The eccentricity of the root of a tree can be computed by the following recurrence relation:

$dTx(x, V(Tx)) = \max\{dTs(s, V(Ts)) + w(x,s)\}, \quad \forall s \in$ *children*(x) and
$w(x,s) \Rightarrow$ weight of edge between node 'x' and its child 's'.

Using the recursive algorithm Eccentricity (T_x), eccentricity can be computed in linear time since each vertex is traversed once. □

Algorithm: Eccentricity (T_x)
Input: A tree $T_x = (V, E)$ rooted at x.
Output: The eccentricity of *node* x in T_x.
Step 1: if x is a leaf then return 0;
Step 2: for each child s of x do
compute Eccentricity (T_s) recursively;
Step 3: return max{Eccentricity(s) + $w(x,s)$}, $\forall s \in$ *children*(x)

Using Lemma 1 and Eccentricity algorithm we find the centre of any tree in polynomial time.

Theorem 1. *A tree can be either unicentric or bicentric.*

Fact 1. *A tree has two or more leaf nodes* [24].

Fact 2. *The maximum distance $d_T(x, V)$ from x to any vertex in tree T, occurs when the vertex is leaf/pendant vertex* [24].

Proof. Deletion of all the leaf nodes results in a graph that is still a tree. Careful observation reveals that the removal of all leaf nodes from tree uniformly reduces the eccentricities of the remaining vertices by one (Fact 1). So all vertices that were centres originally, still remain centres. Continuing this process leaves us with either one vertex which eventually is a centre or an edge whose end points are centres. □

Definition 3 (*Tree Theoretic Centroid (TTCD)*). In a tree '$T(V, E)$', the number of subtrees of any vertex 'v' is equal to its degree and sum of branches (in a subtree) corresponds to the weight of the subtree at 'v'. The weight of the heaviest subtree of vertex 'v' is designated as weight of vertex 'v' and the minimum weighted vertex is designated as Centroid of tree 'T'.

Lemma 2. *Weight of a vertex can be computed in linear time.*

Algorithm: Weight (T_x)
Initialize Main_Root = T_X
Input: A tree $T_x = (V, E)$ rooted at x.
Output: The weight of *node* x in T_x.
Step 1: if x is a leaf then return 0;
Step 2: for each child s of x do compute Weight (T_s) recursively;
Step 3: if (T_S = Main_Root)
Return max{Weight(s) + $w(x,s)$}, $\forall s \in$ *children*(x)
else
return sum{Weight(s) + $w(x,s)$}, $\forall s \in$ *children*(x)

Theorem 2. *Every tree has a centroid consisting of either one vertex or two adjacent vertices.*

Proof. Similar to proof of Theorem 1, by recursive iteration it can be proved that any tree is either unicentroidal or bicentroidal [24]. Hence, we can find centroid of a tree in polynomial time. □

3. System model

We consider a tree $T(V, E)$ which is an ordered pair (V, E), where V = Vertex Set (consisting of $|V|$ vertices) and E = Edge Set (consisting of $|E|$ edges). The distance between two vertices V_i and V_j of any given tree is represented as '$d_T(V_i, V_j)$' and it denotes the shortest path length between the two vertices. The degree '$d(v)$' of a vertex 'v' is defined as number of edges incident to it. A node which has degree one is called as leaf/pendant vertex.

It is known that the number of hop counts is basically determined by a routing scheme which decides the best route from a source to a destination. Also, most routing protocols choose the shortest route which has the smallest number of hop counts. With the increase in number of hops the total time to reach the destination increases. Hence, the performance is measured in terms of delay, the carried load and the total energy consumption which is eventually affected by the average number of hops for message to reach the sink. We therefore address these performance parameters to evaluate our sink placement scheme.

The parameters considered for our observations consider two versions of trees: one that follows a linear arrangement, while the other focuses on the more realistic non-linear arrangement of the nodes. The carried load computations for these strategies can be computed as under Section 4.

4. Carried load calculations

The carried load on the sink is implicative of the total number of data packets received. In contrast, the total load on the nodes is indicative of the total number of packets generated and forwarded for a successful message delivery at the sink. This arrangement of the source to sink communications can pictorially be represented as either a linear or nonlinear topology with different sink placements. Table 1 denotes the graphical representation of the notation used to diagrammatically illustrate the different strategies considered for further analysis.

Table 1 Notations used in diagrams.

Colour	Representation
	TTCT (Tree theoretic centroid)
	TTC (Tree theoretic centre)
	TTC and TTCT coincide

4.1. Linear tree topology strategies

The established tree based topology is classified over three families referred to as case 1, case 2 and case 3 subsequently and is compared to the communication backbone performance with respect to sink at geographical centre or at the end of the region of interest. The placement of sink at different positions in the ROI has been analysed as separate cases.

Strategy 1: The placement of sink at one end of the WSN has been considered as sinks are generally seen at one end of the network which is easily accessible for either data collection or battery replenishment purposes as shown in

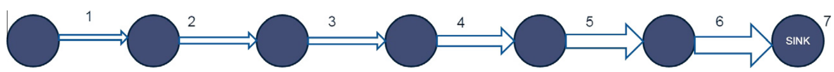

Figure 1 Linear arrangement of sensors with sink at one end.

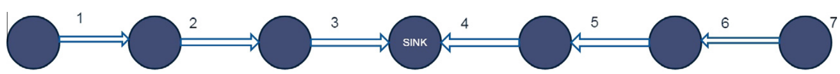

Figure 2 Linear arrangement of sensors with sink at middle.

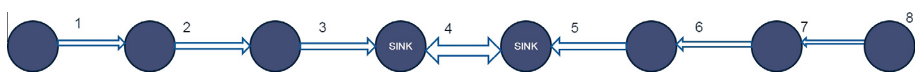

Figure 3 Arrangement of sensors in linear tree topology.

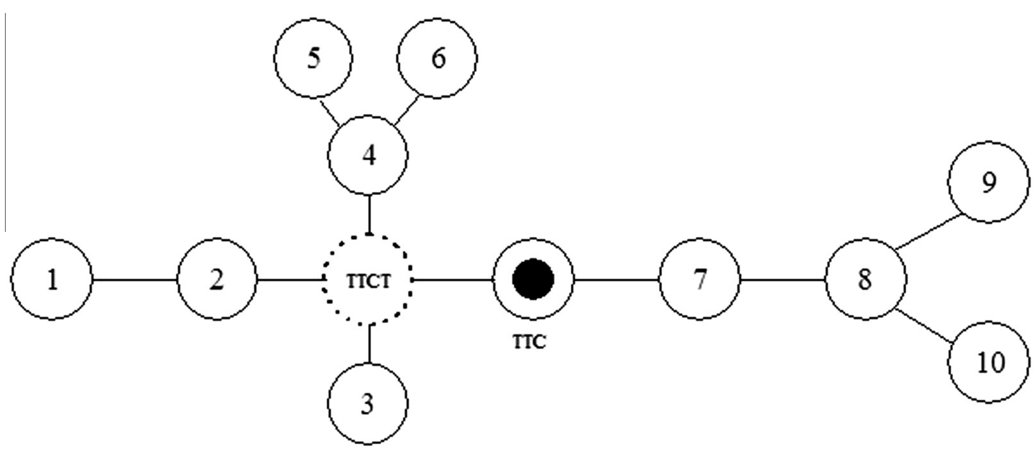

Figure 4a Nonlinear tree topology: TTC and TTCT at different locations.

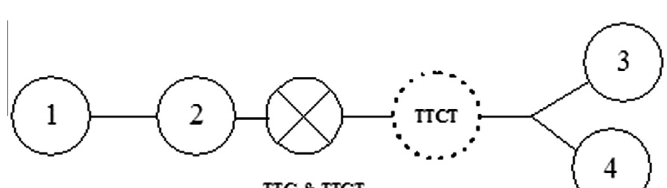

Figure 4b Nonlinear tree topology: TTC and TTCT at different locations; one additional TTCT at different locations.

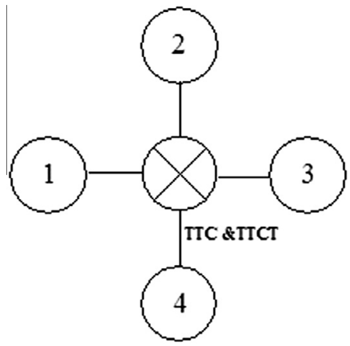

Figure 4c Nonlinear tree topology: TTC and TTCT at same location.

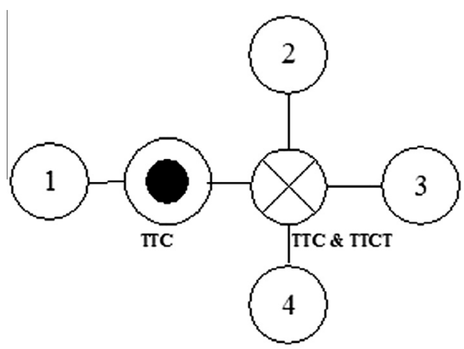

Figure 4d Nonlinear tree topology: TTC and TTCT at same position; additional TTC at different positions.

Fig. 1. Fig. 1 depicts a linear arrangement comprising of seven sensors in which the last sensor (at position 7) acts as the sink. For message communication commencing at Node 1 causes it to generate the first data packet and forward it. Node 2 generates its own packet and forwards two packets (its own and the additional of node 1's that it received). Similarly, node 3 will generate its own and forwards three packets (its own and two from previous nodes). Hence, iteratively the total carried load can be calculated as $C_L = 1 + 2 + 3 + 4 + 5 + 6 + \cdots N - 1$ (where N is total number of sensors).

$$C_L = N * (N - 1)/2 \tag{1}$$

Strategy 2: Placing the sink at some random location in topology is avoided as it is not a desired strategy where results are unpredictable, arbitrary and uncontrolled. Hence, we do not include it for analysis.

Strategy 3: The sink is sited at the centre of the linear topologies considered as given in Fig. 2. Fig. 2 depicts a similar linear arrangement of seven sensors in which middle sensor (at position 4) can act as a sink. Node 1 generates the first packet and forwards it to node 2 which forwards two packets (its own and node 1's received data). This process continues for node 3 similar to case 1. However, Node 7 will forward one, 6 will forward two and 5 will forward three packets to sink. The packet forwarding and aggregation is depicted by the unidirectional arrows. The total carried load can be calculated as $2^*[1 + 2 + 3 + \cdots (N - 1)/2]$.

$$C_L = (N^2 - 1)/4 \tag{2}$$

Strategy 4: Finally placing the sink at the proposed location; the tree theoretic centre (TTC) and centroid (TTCT) as illustrated in Fig. 3. Fig. 3 depicts eight sensors in tree topology which are connected linearly with a maximum of 'one' edge between them. Sensors (at positions 4 and 5) can act as sinks. Total carried load can be calculated as

$$C_L = N^2/4 \tag{3}$$

4.2. Nonlinear tree topology strategies

Figs. 4a–4d depict one representative tree of each scenario in nonlinear tree topology. Fig. 4c is the ideal case where the centre and the centroid coincide and hence our results do not include the trivial proposition.

4.3. Algorithms used

Algorithm: Combined (T_x)
Initialize Main_Root = T_X
Input: A tree $T_x = (V, E)$ rooted at x.
Output: The weight and eccentricity of *node* x in T_x.
1: if x is a leaf then
  Send 0 to parent;
2: for each child s of x do
  Compute Combined (T_s) recursively;
3: Weight$_s$ = sum{Combined(s) + $w(x,s)$}, $\forall s \in children(x)$
Eccentricity$_s$ = max{Combined (s) + $w(x,s)$}, $\forall s \in children(x)$
If (T_S = Main_Root)
Weight$_s$ = max{Combined(s) + $w(x,s)$}, $\forall s \in children(x)$
Send Weight$_s$ and Eccentricity$_s$ to parent node

Algorithm: Sink_Establishment (T_x)
1. For each non-leaf node x of Tree T
2.   Let x be the root
3. Call Combined(T_x)
4.   Broadcast Weight$_x$ and Eccentricity$_x$ to all other non-leaf nodes with its NbrID
5. Centre[ID] = ID of min(Eccentricity$_s$) $\forall z \in non\text{-}leafnode(T)$
6. Centroid[ID] = ID of min(Weight$_z$) $\forall z \in non\text{-}leafnode(T)$
7. SinkID = Intersection(Centre, Centroid)

5. Results

It is assumed that packets are sent to sink via multi-hop communication for energy efficiency in most WSNs. The intermediate sensors act as routers and experience a high packet flow from other sensors and routers. Henceforth, the carried load per node increases and for nodes near the base station or the sink and eventually the packet delivery is delayed considerably. Optimal sink placement results in combating such scenarios. Our aim is to determine the best sited sink among the deployed nodes that conform to tree structured topologies for the reasons best known.

The parameters that have been put to investigation are carried load, average end to end delay and total energy consumption for the key routing protocols namely Ad hoc On Demand Vector based (AODV), Dynamic Source Routing (DSR), Fisheye, Optimised Link state routing (OLSR) protocols [17] depicted by the figures pertaining to the considered cases. To estimate the considered parameters nodes are deployed randomly and individual node statistics are collected over different number of iterations using QualNet simulator 6.0 [25]. QualNet provides a comprehensive environment for employing different protocols, creating and animating network scenarios, and analysing their performance. The nodes are initially deployed randomly and are then arranged in the manner that they topographically resemble the families mentioned. The nodes once arranged approximately to the pattern similar to the figures depicted in Figs. 4a, 4b and 4d are subject to the different routing protocols used in wireless networks. The statistics are collected for 50 topologies for each type of family illustrated and averaged for each one of the three classes; specifically belonging to the nonlinear tree topologies. The conclusions based on the average values of the 50 topologies were considered.

Assumptions.

- The nodes are location aware and a preconstructed tree based communication backbone exists among them.
- The average end to end delay is dependent on the number of hops undertaken for the message to finally reach the sink.
- The energy consumed is the sum of the total energy spent in communicating and receiving. The energy spent during the idle and sleep period is negligible.
- The simulation parameters are given in Table 2.

The first case considers a graph with ‘one’ Tree Theoretic Centre and ‘one’ Tree Theoretic Centroid at two different node locations. The second case analyses a graph with ‘one’ Tree Theoretic Centre and ‘two’ Tree Theoretic Centroid where centre overlaps one centroid while the third case observes a graph with ‘two’ Tree Theoretic Centres and ‘one’ Tree Theoretic Centroid where one of the centre overlaps centroid.

Fig. 5(a), (b) and (c) depict the average hop counts for each protocol. We confirm that the number of hop counts is significantly less in our proposed sites (centre and centroid) for all the protocols considered as compared to the average hop count in case we place the sink at the end or at the

Table 2 Simulation parameter.

Parameters	Values
Radio type	802.11b
Routing protocols	AODV, DSR, FISHEYE, OLSR
Network size (ROI)	1500 × 1500
Node type	Mica motes
Battery model	Residual life estimator
Path loss model	Two Ray
Sensing range	10 m

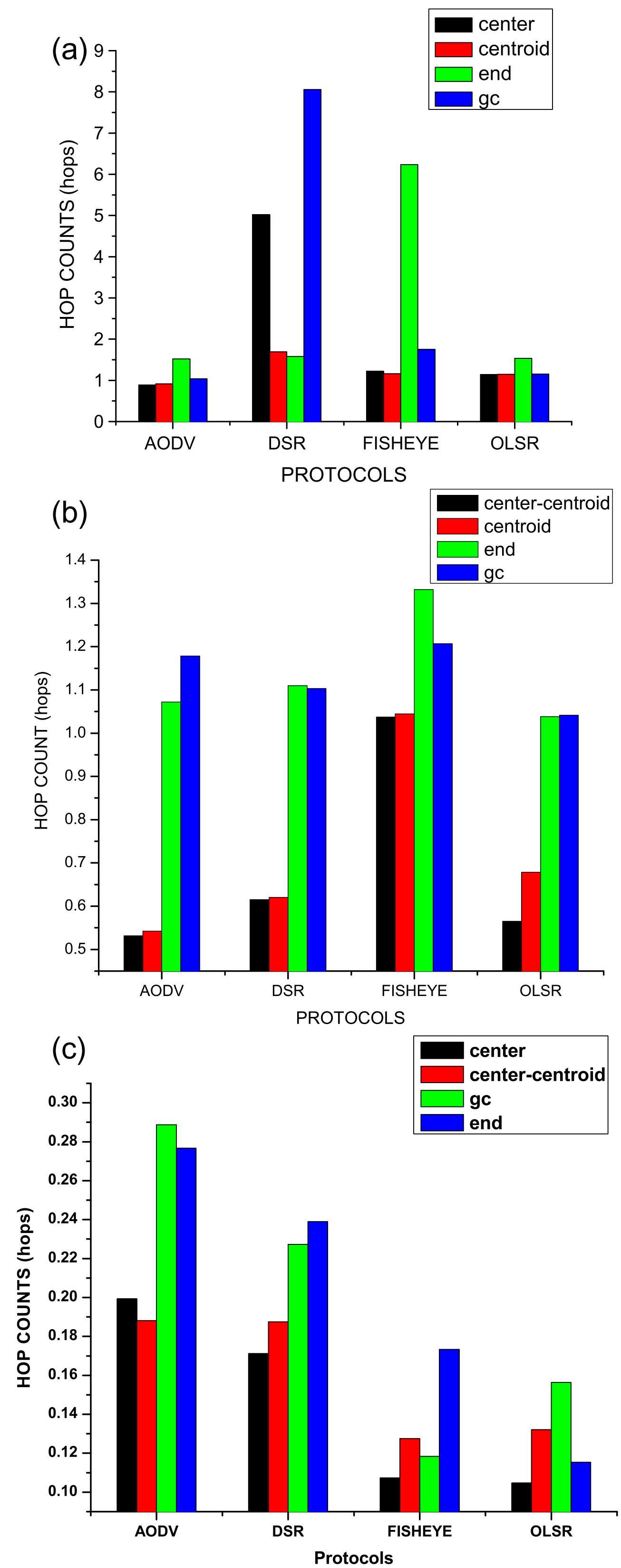

Figure 5 Average hop counts for each protocol (a) Case 1 (b) Case 2 (c) Case 3.

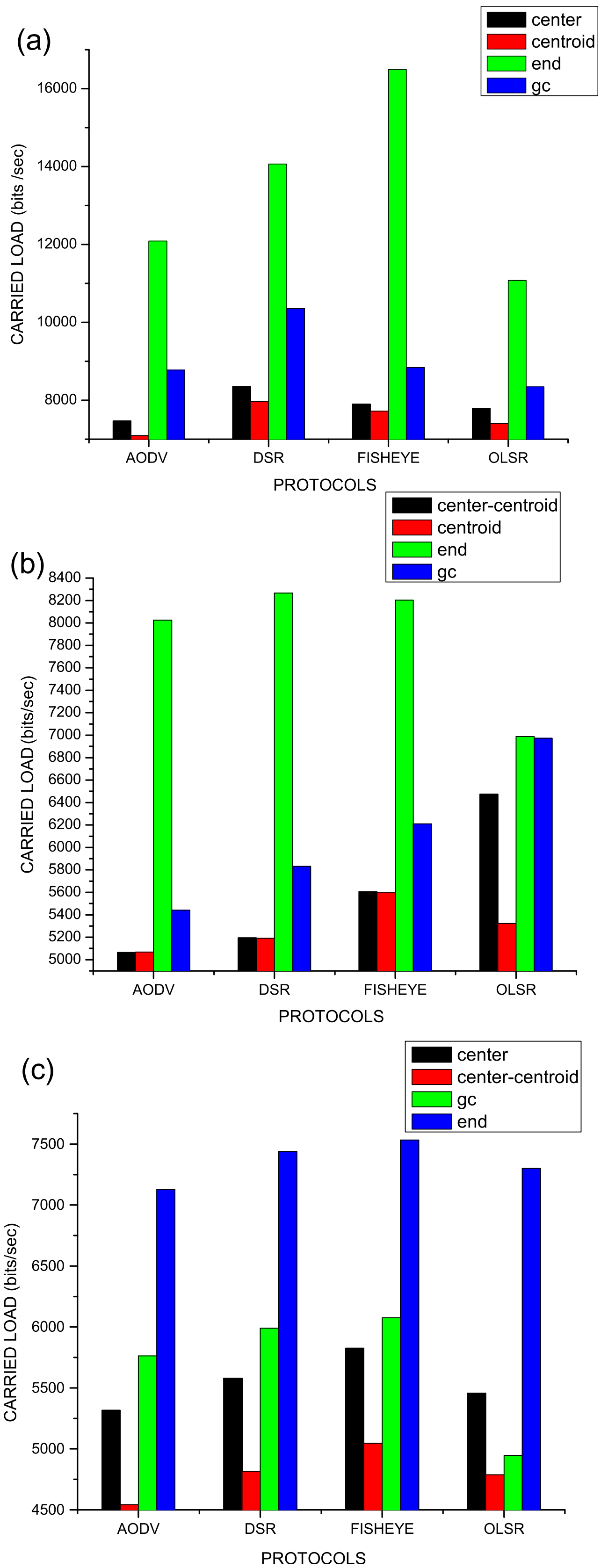

Figure 6 Total carried load for each protocol (a) Case 1 (b) Case 2 (c) Case 3.

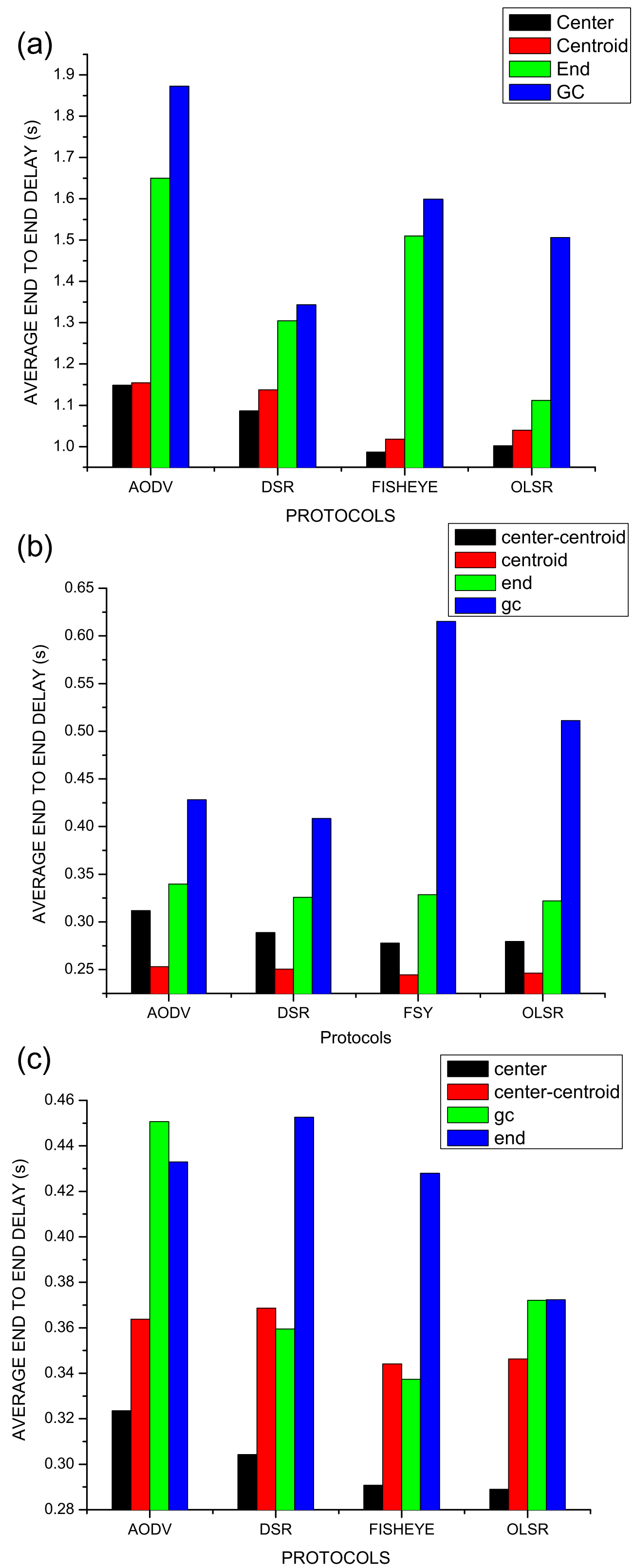

Figure 7 Average end to end delay for protocols (a) Case 1 (b) Case 2 (c) Case 3.

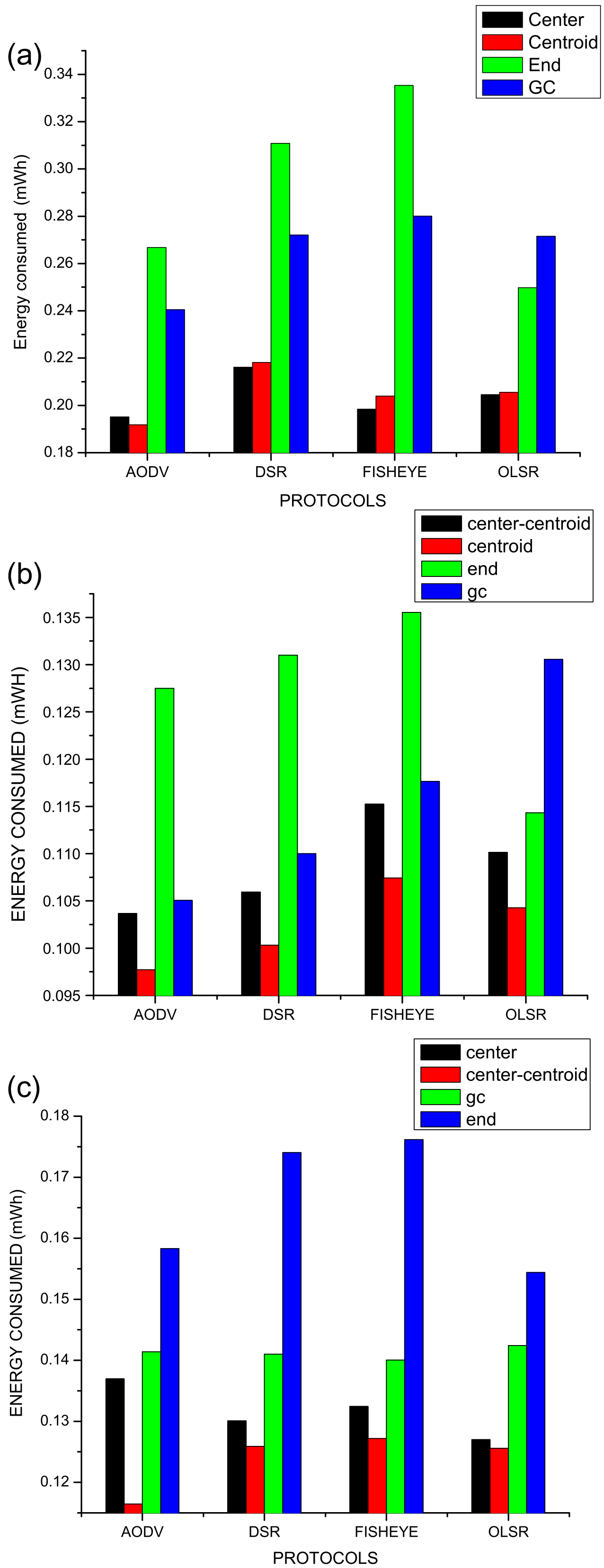

Figure 8 Total energy consumed under each protocol (a) Case 1 (b) Case 2 (c) Case 3.

geographical centre. As the number of hop counts is less, the carried load per node, as well as the end to end delay is largely reduced. This explanation is supplemented by graphical results in Fig. 6(a), (b) and (c) which depict the carried load per node and Fig. 7(a), (b) and (c) which depict the end to end delay respectively. In addition, if the nodes receive and transmit lesser number of packets routed to them, the average energy consumption of the network as a whole is also quite less as depicted in Fig. 8(a), (b) and (c). The different topology scenarios generate almost similar results which induce us to consider their average values for the sake of avoiding redundancies in the graphs. We observe consistent results for all the three cases considered where the adoption of best suited placement of the sink falls either at the centre or at the centroid of the graph. Thus our findings obliterate the requirements to place a sink centrally or at the end of the region of interest.

6. Conclusion

Typical WSN scenarios assume the message routed towards the sink that usually is the root of the tree. This strategy suffers from the problem of hot spots ending into communication disruption due to single node failure closest to the sink. Adopting a graph based topology offers us the choice of variable routes and sink placement which usually turns out to be the geographical centre or the end of the region under observation. The argument biasing this structure is based on achieving maximal coverage under one sink. However, our article confirms that graph centroid placement of the sink node is better in terms of network delay and energy consumption rather than having a sink rooted tree for a communication backbone. Also, our results show that the message forwarding to the sink (in terms of the hop count) is the least for either the graph theoretic centre or centroid. This ensures minimum delay and lesser energy consumption per node and hence a longer lifetime. Our results are limited due to the simulation environment constraints for small number of nodes. This work may be extended by incorporating a wider network with dense deployment. The poor performance of the Fisheye protocol motivates us to analyse our proposed work for incorporating mobility in future.

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