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Extending the Lifetime of Wireless Sensor Networks: A Hybrid Routing Algorithm

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Abstract

Power-aware routing in Wireless Sensor Networks (WSNs) focuses on the crucial problem of extending the network lifetime of WSNs, which are limited by low-capacity batteries. However, most of the contemporary works fail to resolve the hotspot problem, which is the isolation of the sink node due to the power exhaustion of sink close-by nodes. In this paper we propose a solution to address this issue through a hybrid approach that combines two routing strategies, flat multi-hop routing and hierarchical multi-hop routing. The former aims to minimize the total power consumption in the network, and the latter attempts to decrease the amount of traffic by utilizing data compression. We demonstrate through extensive simulations that the proposed scheme is able to extend the network lifetime by alleviating the hotspot problem.

Keywords: Wireless Sensor Networks (WSN), power-aware routing, hotspot, and hybrid.

1. Introduction

In recent years, the rapid development of wireless communications technology, and the miniaturization and low cost of sensing devices, have accelerated the development of Wireless Sensor Networks (WSNs) [1, 2, 3]. A WSN is a group of small sensors-equipped and transmission-capable devices that are deployed in great numbers to monitor areas of interest. WSNs have a wide range of applications from military, which include monitoring adversary behavior, to geographic ones, which include collecting environmental data from tropical rain forests. The general structure of a WSN is composed of a set of sensor nodes and a sink node. The role of sensor nodes is to gather data from their surroundings and transmit it to the sink node. In addition, the sensor nodes also assume the data relay role, in order to compensate the infrastructureless nature of the network, where nodes act as routers that forward data for other sensor nodes. On the other hand, the general role of the sink node is to act as a data assembly point from which data is extracted from the network.

A significant limitation in current sensor nodes is low battery capacity, consequently, efficient use of the sensor node's energy reserve is essential. The sensor node utilizes its built-in battery for communication and sensing, in the occasion of battery's exhaustion, the sensor's functionality completely halts, inevitably leading to losing parts of the network's functionality, also note that changing the batteries of large numbers of sensor nodes over wide areas with potentially unsafe terrain, as in military applications, or difficult to reach areas, as in underwater monitoring applications, is practically infeasible. Consequently, much research effort has been focused on maximizing the lifetime of the wireless sensor networks.

The objective of our research is to extend the lifetime of the network via a better routing algorithm. In particular, we are interested in the isolation of the sink node caused by the depletion of the energy of sensor nodes surrounding it; this problem is termed as the hotspot problem. It is of prime importance because in the event that the sink node is isolated from the network, the rest of the network will be rendered useless.

The severeness of the hotspot problem differs substantially whether the sensor nodes and/or the sink node are mobile or not. In the case where the sink node is mobile, as in [4, 5, 6, 7], the sink node moves around the sensing area and collects data from the sensor nodes, thus effectively balancing the energy consumption in the WSN. The sensor nodes can transmit the data periodically (e.g., as in applications that are not delay tolerant), or store the data and delay the transmission till the displacement between the senor nodes and the mobile sink node is minimal to decrease the power consumed while relaying data to the sink. In the case where sensor nodes are mobile, as in [8, 9], the nodes can adjust their position to help balance energy consumption in areas that have high transmission load and/or mitigate network partition. Deploying a mobile sinks and nodes will increase the WSN's deployment costs. Additionally, in some applications mobility is impractical. In

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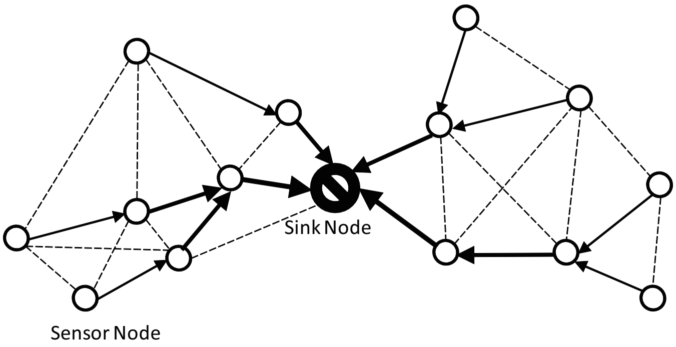


Figure 1: Flat multi-hop routing.

this paper, we consider the challenging case where the sink and sensor nodes are immobile, propose a routing algorithm, and demonstrate its effectiveness through extensive computer simulations. The rest of this paper is organized as follows. Section II introduces multi-hop routing algorithms for WSNs, accompanied by an examination of the hotspot problem. In Section III, we present our proposed method that rectifies the hotspot problem. Followed in Section IV with performance evaluation of our proposed method. We finalize in Section V with a conclusion.

2. Multi-hop routing algorithms for wireless sensor networks

The basic function of a routing algorithm is to select the path from a set of available paths that is most efficient based on a specific criteria. Intuitively, to maximize the WSN's network lifetime, the path that achieves minimum power consumption while ensuring fair power consumption among individual nodes should be used. Much effort has been focused on WSN multi-hop routing algorithms, and many algorithms have been proposed [10, 11, 12, 13]. These may be widely categorized as flat multi-hop routing algorithms and hierarchical multi-hop routing algorithms. In the upcoming subsections, we present a discussion of them.

2.1. Flat Multi-hop routing algorithms

In Fig.1, an illustration of how flat multi-hop routing algorithms are used to send data is shown. In the illustration, each sensor node has the ability to communicate over a bounded area within its maximum transmission range to other sensor nodes, and an arrow's thickness is proportional to the amount of data being transmitted over that corresponding link. In practice, link utilization differs greatly between different routing algorithms. For example, algorithms proposed in [14, 15] have been designed to minimize the total power consumption of the network as an objective, in this kind of algorithms the cost of using a communication channel is defined by the following equations.

$$linkcost(i,j) = e_s(i) + e_r(j) \tag{1}$$

$$e_s(i) = \epsilon_1 d_{i,j}^2 + \epsilon_2 \tag{2}$$

$$e_r(j) = \epsilon_3. \tag{3}$$

Here, $linkcost(i,j)$ is defined as the amount of energy consumed for sending a unit of data from the transmitting node i to the receiving node j. $e_s(i)$ is the energy consumed by the transmitting node i for sending a unit of data to the receiving node j, this value is proportional to the square of the distance between the transmitting node i and the receiving node j. e_r is the energy consumed by the receiving node j in order to receive a unit of data, it is worth noting that this energy consumption is constant. ϵ_1, ϵ_2, and ϵ_3 are constant parameters that are characteristic of the sensor node's transmitting and receiving circuitry. By using the route where the sum of all link costs is minimum, the WSN's total power consumption can be minimized. While the above definition of $linkcost(i,j)$ successfully decreases the total power consumption of the WSN, inevitability, defining $linkcost(i,j)$ in this manner would over-exhaust certain nodes, thus resulting in rapid consumption of their energy. An effective algorithm [16], which uniformly distributes power consumption over each node, aims to address this problem by redefining $linkcost(i,j)$. The following equation is used to define the link cost.

$$linkcost(i,j)_{new} = \frac{linkcost(i,j)}{E_i^n} \tag{4}$$

By using the residual energy of the sending node as denominator of $linkcost(i,j)$, the possibility of being selected as a relay node decreases as its remaining energy diminishes. For example Toh [16] set n to be 2. Thus, it is possible to uniformly distribute power consumption over individual nodes and at the same time to minimize total power consumption. Other than the previously mentioned algorithm, other algorithms have also been proposed such as zP_{min} [17] and max–min T [18, 19, 20, 21].

2.2. Hierarchical multi-hop routing

Flat multi-hop routing algorithms are excellent in terms of their capability of using power-aware metrics to choose minimum power consuming paths. However they fail to take advantage of the highly correlated nature of the data collected from the WSN. The relatively high node density of the WSN and the application scope of the WSN (e.g., temperature readings collected from geographically close locations have a high probability of becoming similar), make data aggregation a very attractive technique in WSN. Hierarchal multi-hop routing algorithms successfully utilize the data aggregation to decrease the volume of data flowing in the network. In hierarchical multi-hop routing algorithms, sensor nodes assume different roles, which can be changed with time. Here, we briefly review the most notable example of hierarchical multi-hop routing algorithms, dubbed Low-Energy Adaptive Clustering Hierarchy (LEACH) [22], as an example for illustration.

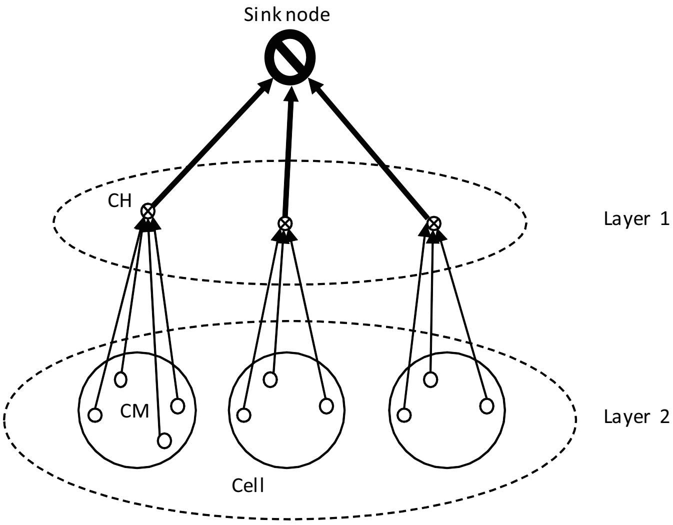
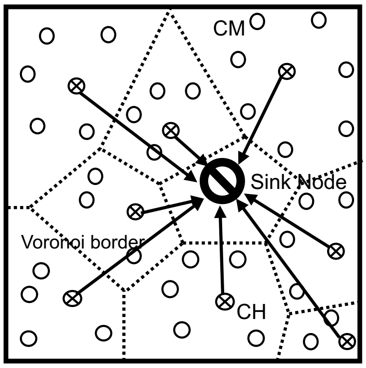


Figure 2: Hierarchical multi-hop routing.

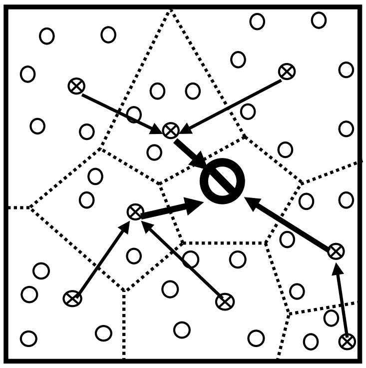
LEACH is a two-layered hierarchical multi-hop routing algorithm, as shown in Fig.2. Each node can play the role of a Cluster Head (CH) or Cluster Member (CM). In addition, each node's role can be renewed in a time interval, referred to as a round. At the beginning of each round, each node can declare itself as a CH with a certain probability; otherwise the node behaves as a CM. The network is divided into a number of clusters, referred to as cells, this division corresponds to Voronoi partitioning with each individual CH located in the center of its cell, as illustrated in Fig. 3(a). CM(s) choose the CH that are closest to it, i.e., lies within its cell, and each CH and CM(s) form a cluster, CMs transmit the data they collected to the CH that controls the cell to which they belong to, then each CH compresses the data received from the CM(s), and sends it to the sink node.

In LEACH, since CHs initiate communication directly to the sink node, the transmission distance between CHs and the sink node tends to be large, thus causing rapid battery drain. Many multi-hop variants of LEACH [23] have been proposed and aim to mitigate this issue, Fig. 3(a) and Fig. 3(b) illustrates the differences between LEACH and the multi-hop variants of LEACH. In the multi-hop variants of LEACH, by performing inter-cluster communication by CHs in a multi-hop manner, the power consumption attributed to CH-to-sink communication can be substantially decreased.

While, CHs are determined randomly in LEACH. More intuitive selection methods can yield dividends in terms of decreased power consumption. For example, In HEED [24], the CH selection method is based on nodes proximity to its neighbors, in addition to the residual energy of the node, nodes that have a higher score of the these two metrics have a higher probability of being chosen as a CH. By doing so the communication distance between CH and CMs can be decreased, and thus resulting in reduction of power consumption in each cluster. In PEACH [25], by increasing the probability of the node with the highest remaining power to become a CH, fairness in power consumption can be improved. In hierarchical multi-hop routing algorithms, since the number of relay nodes, i.e., hops, used to convey data to the sink node is relatively less than that in flat multi-hop routing algorithms, the length of the communication distance of each hop becomes greater than that in flat multi-hop routing algorithms, and thus requiring higher power to transmit a unit of data. Nevertheless, hierarchical multi-hop routing algorithms are a promising approach in terms of their capability of using data compression to efficiently reduce the amount of data transmitted over the network, and thus reducing the total power consumption in the network.



(a) LEACH.



(b) Multi-hop variants of LEACH.

Figure 3: Comparison between LEACH and its multi-hop variants.

2.3. Hotspot problem in wireless sensor networks

We define the hotspot problem as the isolation of the sink node from the rest of the network as a result of the power exhaustion of nodes in the hotspot area. In this paper, the area in the interior of the maximum transmission distance of the sink node is defined as the hotspot area, as shown in Fig. 4. Owing to the many-to-one(convergecast) traffic patterns in sink-based WSN, since the sensor nodes which are close to the sink node transmit a larger amount of data than the nodes further away from the sink, as shown in Fig. 1, they exhaust their energy in a much more

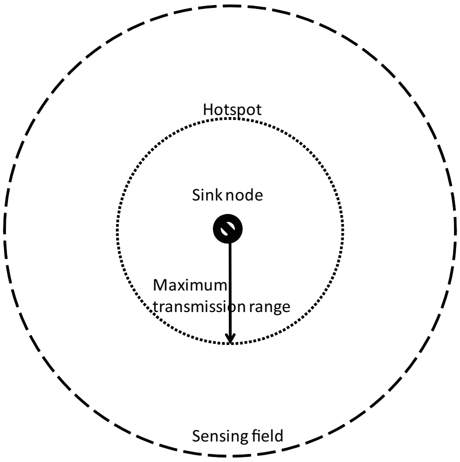


Figure 4: Definition of hotspot area.

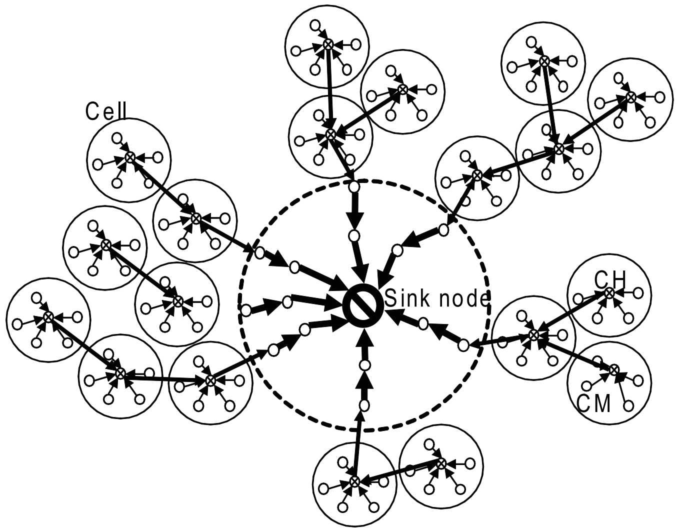


Figure 5: Hybrid multi-hop routing.

rapid manner, and die promptly. When all of nodes located in the hotspot area die, it is impossible to gather data from a large number of alive nodes, due to the lack of available routes between the sink node and the nodes outside of the hotspot area, despite the abundance of residual energy in the network, in fact [26] argues that by the time that sensor nodes one-hop away from the sink node exhaust their energy, sensors farther away can have up to 93% of their initial energy. In other words, to evaluate the network lifetime in a more meaningful manner, it is essential to take into account the influence of the hotspot problem. While most of previous works have just only investigated the time change of the surviving rate of nodes in the network or the time the first node dies. Therefore, we propose an algorithm designed with the consideration of the impact of the hotspot problem in order to achieve an extension of the functional network lifetime.

3. Hybrid multi-hop routing algorithm

In general, since the number of sensor nodes in the hotspot area is much smaller than the nodes that are outside the hotspot area, consequently, the amount of data generated by the nodes in the hotspot area is negligible as compared to the volume of data flowing into the hotspot area from outside the hotspot area, implying that most of the power consumption in the hotspot area is due to relaying the data that came from outside the hotspot area. That is to say, that in order to decrease the power consumption in the hotspot area, the amount of data flowing into the hotspot area needs to be reduced, and/or the power consumption to relay a unit of data from outside the hotspot to the sink node needs to be minimized. In fact, our proposed scheme aims to achieve the effect of both solutions by adopting the hybrid multi-hop routing algorithm, which employs a hierarchical multi-hop routing algorithm outside the hotspot area to decrease the inflow of data flowing to the hotspot, and uses a flat multi-hop routing algorithm inside the hotspot area to decrease the transmission distance of nodes in hotspot area.

3.1. Routing outside the hotspot area

Since the transmission power is proportional to the volume of data, it is important to reduce the volume of data that enters the hotspot area, this can be achieved by using a data compression mechanism. If there is any relationship between the collected data, it can be compressed. The compression ratio is dependent on the correlation of the data, i.e, the higher the data is correlated the more effective data compression can be. For example, in the case of environment monitoring which collects information on temperature, humidity, and atmospheric pressure, it has been widely known that data collected from neighboring areas has a high probability of being strongly correlated, which can lead to a high compression ratio. From the above discussion, the proposed scheme employs a hierarchical multi-hop routing algorithm outside the hotspot, which is an appropriate strategy to perform efficient data compression so as to reduce the amount of data flowing into the hotspot area.

3.2. Routing inside the hotspot area

In the hotspot area, the most important aspect of a routing algorithm is to minimize the power consumption per unit of transmission while transferring the data coming from outside of the hotspot area to the sink node. Fortunately, this can be readily achieved by adopting a flat multi-hop routing algorithm in the hotspot area to utilize the efficient transmission distances characteristic to it.

3.3. Analyzing power consumption in the hotspot

We aim to mathematically analyze the energy consumption of the hotspot. The model we adopt is shown

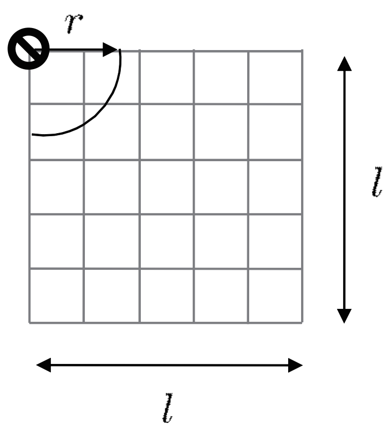


Figure 6: Considered mathematical analysis.

in Fig. 6. As discusses above, the hotspot energy consumption attributed to sending data originating from inside the hotpsot is insignificant as compared to the energy consumed for relaying data flowing into the hotspot from outside. Hence the energy consumption formulates to:

$$E^{Hotspot} = \lambda \times E(d) \times M, \tag{5}$$

where λ denotes the average number of hops the data has to be relayed through in hotspot to reach the sink, $E(d)$ is the energy consumed to transmit a unit of data over a distance, d, which is the average transmission distance, and M is the volume of data. These terms are expresses as:

$$\lambda = \frac{r}{d}, \tag{6}$$

where r is the hotspot radius. $E(d)$ can be derived from Eq. 2, also, since $\epsilon_1 \ggg \epsilon_2$, $E(d)$ amounts to,

$$E(d) = \epsilon_1 d^2, \tag{7}$$

The volume of data flowing into the hotspot, M, can be derived as shown:

$$M = mN(1 - \frac{\pi r^2}{4l^2}). \tag{8}$$

Here, m is the message size, N is the number of nodes in the network, and l is the length of the area. Finally, $E^{Hotspot}$ formulates to:

$$\begin{aligned} E^{Hotspot} &= \frac{r}{d} \times \epsilon_1 d^2 \times mN(1 - \frac{\pi r^2}{4l^2}) \\ &= \epsilon_1 mrdN(1 - \frac{\pi r^2}{4l^2}). \end{aligned} \tag{9}$$

The above equation gives a general framework that shows the hotspot energy consumption for all kinds of routing algorithm. To accommodate the differences in routing algorithm we express the energy consumption for the two contemporary categories of multi-hop routing algorithm

Table 1: Configuration of simulation environment.

Parameter	Value
ϵ_1	2×10^{-7} [J/packet/m^2]
ϵ_2, ϵ_3	2×10^{-6} [J/packet]
Data compression rate (μ)	0.7
Probability selected as CH	0.2
Time interval of each round	10 [s]
Number of nodes	500
Maximum transmission range	600 [m]
Data transmission rate	1 [packet/round]
Initial energy	1000 [J]

and our proposed multi-hop routing algorithm, as follows:

$$E^{Hotspot}_{Flat} = \epsilon_1 mrd_{Flat} N(1 - \frac{\pi r^2}{4l^2}) \tag{10}$$

$$E^{Hotspot}_{Hierarchical} = \epsilon_1 mrd_{Hierarchical} \sigma N(1 - \frac{\pi r^2}{4l^2}) \tag{11}$$

$$E^{Hotspot}_{Hybrid} = \epsilon_1 mrd_{Flat} \sigma N(1 - \frac{\pi r^2}{4l^2}), \tag{12}$$

where $d_{Flat}, d_{Hierarchical}$ are the average transmission distances for nodes when flat and hierarchical multi-hop routing algorithms, respectively. These can be derived from node density, N/l^2 and CH ratio. σ is the compression rate, defined as:

$$\sigma = \frac{Size[Compressed\,Data]}{Size[Original\,Data]}. \tag{13}$$

From Eq. 11-12, the dividends gained from employing hybrid multi-hop routing can be assisted. Since CHs are generally less in number than the total number of nodes in the WSN, renders $d_{Flat} < d_{Hierarchical}$. Furthermore, $0 < \sigma < 1$, thus we can conclude that:

$$E^{Hotspot}_{Hybrid} < E^{Hotspot}_{Flat} \tag{14}$$

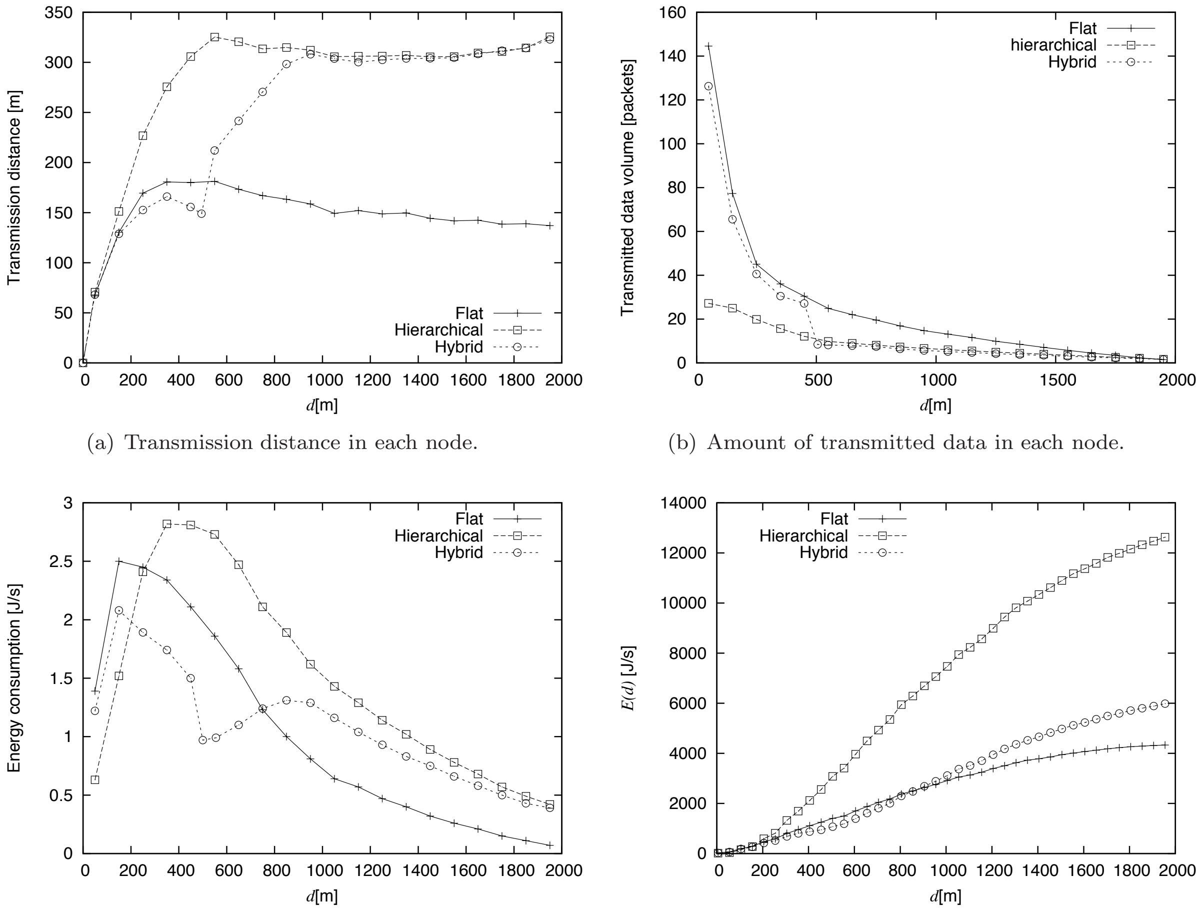
$$E^{Hotspot}_{Hybrid} < E^{Hotspot}_{Hierarchical} \tag{15}$$

From Eq. 15 and Eq. 15, we have showed that our proposed hybrid multi-hop algorithm yields less power consumption in the hotspot as compared to the two contemporary categories of multi-hop routing algorithm. Additionally, observing the ratio between Eq. 12 and Eqs. 11 12 gives insight at the difference in energy consumption between our proposed hybrid multi-hop routing algorithm and the other two categorizes of multi-hop routing algorithm, as shown below,

$$\frac{E^{Hotspot}_{Hybrid}}{E^{Hotspot}_{Flat}} = \sigma < 1 \tag{16}$$

$$\frac{E^{Hotspot}_{Hybrid}}{E^{Hotspot}_{Hierarchical}} = \frac{d_{Flat}}{d_{Hierarchical}} < 1. \tag{17}$$

Implying that the ratio of energy consumption in our proposed hybrid multi-hop routing algorithm depends only



(a) Transmission distance in each node.

(b) Amount of transmitted data in each node.

(c) Energy consumption in each node.

(d) Energy consumption in network.

Figure 7: Performance comparison among three different routing algorithms.

on two factors, i.e., σ and $d_{Flat}/d_{Hierarchical}$. We further continue our evaluation of our proposed hybrid multi-hop routing algorithm in the following section.

Table 2: Network lifetime comparison.

Flat	Hierarchical	Hybrid
4838 [s]	3974 [s]	5397 [s]

4. Performance evaluation

4.1. Experiment contents

In this section, we aim to evaluate the performance of our proposed algorithm to extend the lifetime of the WSN by dealing with the hotspot problem. For evaluation, Network Simulator version 2 (NS2) [27] is used to carry out our experiments. Table 1 exhibits the configuration of the simulation environment where values of each parameter are set according to the configurations adopted in references [16, 22]. Sensor nodes are randomly deployed in the circular sensing field centered on the sink node. Since the nodes have a maximum transmission range of 600m, the hotspot area is a circular area centered on the sink with a radius of 600m. The sensing field radius is set to a relatively high value of 2000m. The experiment is set up so that each sensor node in the network generates a single packet periodically, and all packets are transmitted to the sink node. Each experiment has been performed twenty times, and all of the results illustrated in graphs represent the averaged value for all different node arrangements.

We assume that nodes are distributed without large deviation of node density, i.e., the number of nodes in the hotspot area does not deviate much from run to run to accurately study the power consumption in the hotspot area. In this experiment to illustrate our proposed technique, a multi-hop variant of LEACH and Toh's method have been employed outside the hotspot area and inside the hotspot area, respectively. Also, these two notable multi-hop routing algorithms have been used as representatives for comparison of the two contemporary classes of multi-hop routing algorithm, flat and hierarchical.

The remainder of this section is divided into two subsections. In the first subsection, we show the superiority of our proposed hybrid multi-hop routing algorithm with respect to the two contemporary classes of multi-hop routing algorithms, by inspecting numerous metrics. In the second subsection, we investigate the hybrid boundary, which is the point where the employed multi-hop routing algorithm is changed from flat to hierarchical and vice versa, this boundary determines how big the areas where sizes of where flat and hierarchal multi-hop routing algorithms are employed.

We consider using energy consumption in the hotspot area and network lifetime as performance metrics. Network lifetime is defined as the time when all the nodes in the hotspot area have exhausted their power capacities, at this time the sink node is completely isolated from the majority of nodes in the network, which lie outside the hotspot.

4.2. Performance comparison

We set the hybrid boundary of our proposed algorithm to 500m, the reason for this will be explained in the following subsection. To compare our hybrid multi-hop routing algorithm with respect to both flat and hierarchical multi-hop routing algorithms we considering numerous metrics, as follows.

Fig.7(a) depicts the averaged transmission distance of each node located d meters away from the sink. It can be obviously observed that the hierarchical multi-hop routing suffers from a larger transmission distance as compared with the flat multi-hop routing. In addition, it should be noted that, in our proposed method, the communication distance is entirely different between the outside and the inside of the hotspot area due to the difference in the adopted algorithm in each area. It can be noticed that at the hybrid boundary (d=500), the transmission distance fluctuates. The reason behind it, is that the alteration of the employed routing algorithm occurs at that point.

Fig. 7(b) depicts the average volume of transmitted data of each node located d meters away from the sink, it is clear that the flat multi-hop routing algorithm incurs the highest volume of transmitted data when compared with the two other multi-hop routing algorithm categories. Also, the volume of data relayed increases as d gets closer to the sink node. At the hybrid boundary, the rate of data relay changes, due to the lack of data compression in the routing algorithm employed inside the hybrid boundary. Our proposed algorithm successfully utilizes data compression to limit the flow of data in the network.

Fig. 7(c) shows the individual power consumption of nodes located d meters away from the sink. The energy consumption increases as the node's position gets closer the sink, and it reaches its maximum with nodes inside the hotspot. It can also be noticed that hybrid boundary causes changes in the pattern of energy increase. Evidently, our proposed hybrid multi-hop routing algorithm minimizes the individual power consumption of nodes in the hotspot area.

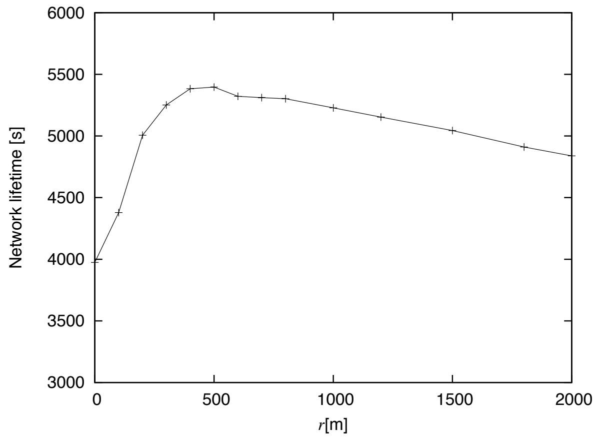
In Fig. 7(d), $E(d)$ indicates the cumulative power consumption in the circular area centered on the sink node with the radius equal to d. The result validates that our proposed hybrid multi-hop routing algorithm can minimize the total power consumption in the hotspot area. In addition, as evident from the network lifetime as summarized in Table 2, the proposed method consequently succeeds in prolonging the network lifetime substantially by avoiding sink node isolation caused by the power exhaustion of all nodes in the hotspot area.

4.3. Considering the hybrid boundary location on performance

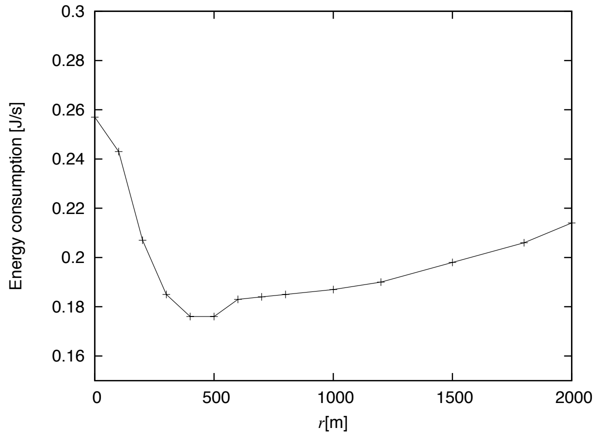
In this subsection, we consider the influence of hybrid boundary location on the performance of the proposed hybrid routing algorithm. The choice of hybrid boundary depends on the characteristics of the flat and hierarchical multi-hop routing algorithm employed and the environment. Fundamental analysis of our proposed hybrid multi-hop routing algorithm has been proposed Sec. 3.3, as future work, we aim to analyze the effect of r on $E^{Hotspot}$. In this paper, we adopt an experimental approach towards investigating the effect of r. The distance between the sink node and the hybrid boundary, r, is varied and the changes in the network lifetime and the power consumption in the hotspot area are examined. From Fig. 8, it is very evident to see that the network lifetime is maximized when the hotspot area's power consumption becomes minimum. Intuitively, the optimal hybrid boundary exists in the hotspot area, i.e., r is equal to 500m (less than 600m). Fig. 9 depicts how the hybrid multi-hop algorithm performance behaves for different values of hybrid boundaries, i.e., r is set to 400m, 500m, and 600m. The metrics considered are, the average transmission distance, the average energy consumption, and the average transmitted traffic volume of each node located at d meters away from the sink node. The energy consumption, achieves its minimum when the combination between volume of relayed data and transmission distance is minimum occurring at r equal to 500. From the above consideration, the previous experiments used 500m as the value of hybrid boundary to evaluate the performance of the proposed algorithm.

5. Conclusion

In this paper, we have proposed a hybrid multi-hop routing algorithm, which prolongs the network lifetime of wireless sensor networks by coping with the hotspot problem. Existing routing algorithms developed for wireless sensor networks can be categorized into two classes, flat multi-hop routing algorithms which minimize the total power consumption in the entire network and hierarchical multi-hop routing algorithms which efficiently reduce the amount of traffic flowing through the network by using data aggregation mechanism; both approaches do not take into account the network isolation caused by the



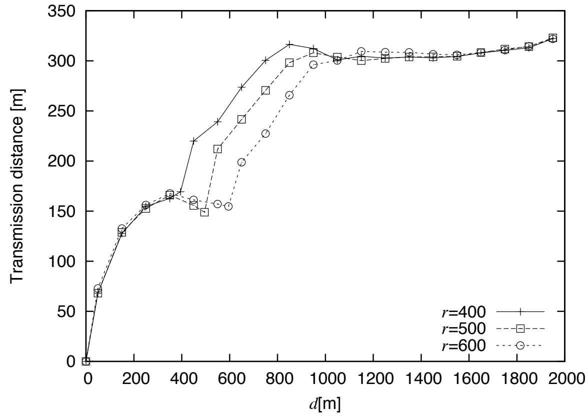
(a) Effect of hybrid boundary on network lifetime.



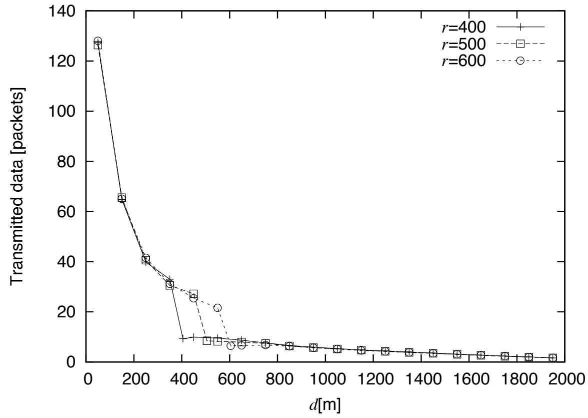
(b) Effect of hybrid boundary on energy consumption in the hotspot.

Figure 8: Performance of hybrid multi-hop routing algorithm under different hybrid boundary.

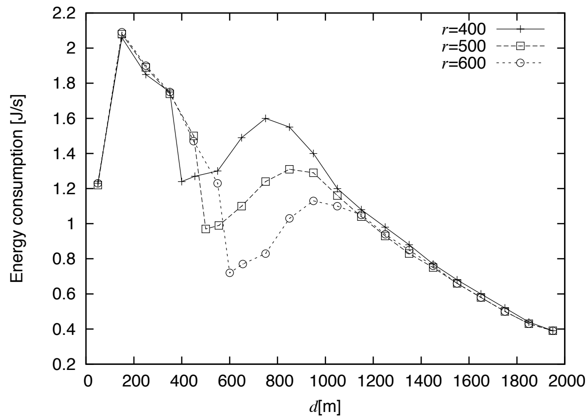
hotspot problem, which is defined as the isolation of the sink caused by the battery exhaustion of nodes around it. To tackle this issue, we have proposed the hybrid mutli-hop routing algorithm by combining flat and hierarchical multi-hop routing algorithms. Through rigorous computer simulations, we analyze our proposed multi-hop routing algorithm with regards to various metrics, and evaluate its performance. Finally, it can be concluded that the hybrid multi-hop routing algorithm is a promising solution for the hotspot problem and extending the network lifetime.



(a) Transmission distance in each node.



(b) Amount of transmitted data in each node.



(c) Energy consumption in each node.

Figure 9: Performance under different boundaries in hybrid routing.

References

[1] Akyildiz, I., Su, W., Sankarasubramaniam, Y., Cayirci, E., Aug. 2002. A survey on sensor networks. Communications Magazine, IEEE 40 (8), 102 – 114.

[2] Yick, J., Mukherjee, B., Ghosal, D., 2008. Wireless sensor network survey. Computer Networks 52 (12), 2292 – 2330.

[3] Tubaishat, M., Madria, S., 2003. Sensor networks: an overview. Potentials, IEEE 22 (2), 20 – 23.

[4] Nakayama, H., Ansari, N., Jamalipour, A., Nemoto, Y., Kato, N., 30 2007-may 2 2007. On data gathering and security in wireless sensor networks. In: Sarnoff Symposium, 2007 IEEE. pp. 1 –7.

[5] Nakayama, H., Ansari, N., Jamalipour, A., Kato, N., 2007. Fault-resilient sensing in wireless sensor networks. Computer Communications 30 (11-12), 2375 – 2384, special issue on security on wireless ad hoc and sensor networks.

[6] Luo, J., Hubaux, J.-P., 2005. Joint mobility and routing for lifetime elongation in wireless sensor networks. In: INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE. Vol. 3. pp. 1735 – 1746 vol. 3.

[7] Shah, R. C., Roy, S., Jain, S., Brunette, W., 2003. Data mules: modeling and analysis of a three-tier architecture for sparse sensor networks. Ad Hoc Networks 1 (2-3), 215 – 233, sensor Network Protocols and Applications.

[8] He, S., Chen, J., Sun, Y., Yau, D., Yip, N. K., Jun. 2010. On optimal information capture by energy-constrained mobile sensors. Vehicular Technology, IEEE Transactions on 59 (5), 2472 –2484.

[9] Cao, X., Chen, J., Gao, C., Sun, Y., September 2009. An optimal control method for applications using wireless sensor/actuator networks. Comput. Electr. Eng. 35, 748–756.

[10] Al-Karaki, J., Kamal, A., 2004. Routing techniques in wireless sensor networks: a survey. Wireless Communications, IEEE 11 (6), 6 – 28.

[11] Luo, H., Liu, Y., Das, S., 2007. Routing correlated data in wireless sensor networks: A survey. Network, IEEE 21 (6), 40 –47.

[12] Khan, I., Javed, M., 2008. A survey on routing protocols and challenge of holes in wireless sensor networks. In: Advanced Computer Theory and Engineering, 2008. ICACTE '08. International Conference on. pp. 161 –165.

[13] Akkaya, K., Younis, M., 2005. A survey on routing protocols for wireless sensor networks. Ad Hoc Networks 3 (3), 325 – 349.

[14] Singh, S., Woo, M., Raghavendra, C. S., 1998. Power-aware routing in mobile ad hoc networks. In: Proceedings of the 4th annual ACM/IEEE international conference on Mobile computing and networking. MobiCom '98. ACM, New York, NY, USA, pp. 181–190.

[15] Rodoplu, V., Meng, T., Aug. 1999. Minimum energy mobile wireless networks. IEEE J. Select. Areas Commun. 17 (8), 1333 – 1344.

[16] Toh, C.-K., Jun. 2001. Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks. Communications Magazine, IEEE 39 (6), 138 –147.

[17] Aslam, J., Li, Q., Rus, D., 2002. Three power-aware routing algorithms for sensor networks. Wireless Communications and Mobile Computing 3, 187–208.

[18] Chang, J.-H., Tassiulas, L., August 2004. Maximum lifetime routing in wireless sensor networks. IEEE/ACM Trans. Netw. 12, 609–619.

[19] Madan, R., Lall, S., 2006. Distributed algorithms for maximum lifetime routing in wireless sensor networks. Wireless Communications, IEEE Transactions on 5 (8), 2185 –2193.

[20] Xue, Y., Cui, Y., Nahrstedt, K., December 2005. Maximizing lifetime for data aggregation in wireless sensor networks. Mob. Netw. Appl. 10, 853–864.

[21] Sankar, A., Liu, Z., 2004. Maximum lifetime routing in wireless ad-hoc networks. In: INFOCOM 2004. Twenty-third AnnualJoint Conference of the IEEE Computer and Communications Societies. Vol. 2. pp. 1089 – 1097 vol.2.

[22] Heinzelman, W., Chandrakasan, A., Balakrishnan, H., Oct. 2002. An application-specific protocol architecture for wireless microsensor networks. Wireless Communications, IEEE Transactions on 1 (4), 660 – 670.

[23] J. Neander, E. Hansen, M. Nolin, and M. Bjorkman, "Asymmetric multihop communication in large sensor networks," in *Wireless Pervasive Computing, 2006 1st International Symposium on*, p. 7 pp., jan. 2006.

[24] Younis, O., Fahmy, S., 2004. Heed: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. Mobile Computing, IEEE Transactions on 3 (4), 366 – 379.

[25] Yi, S., Heo, J., Cho, Y., Hong, J., October 2007. Peach: Power-efficient and adaptive clustering hierarchy protocol for wireless sensor networks. Comput. Commun. 30, 2842–2852.

[26] Wadaa, A., Olariu, S., Wilson, L., Jones, K., Xu, Q., 2003. On training a sensor network. In: Parallel and Distributed Processing Symposium, 2003. Proceedings. International. p. 8 pp.

[27] The Network Simulator - ns-2 [Online]. Available: http://www.isi.edu/nsnam/ns/.