HYMN: A Novel Hybrid Multi-hop Routing Algorithm to Improve the Longevity of WSNs

HYMN: A Novel Hybrid Multi-hop Routing Algorithm to Improve the Longevity of WSNs

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***Abstract*— Power-aware routing in Wireless Sensor Networks (WSNs) is designed to adequately prolong the lifetime of severely resource-constrained ad hoc wireless sensor nodes. Recent research has identified the energy hole problem in single sink-based WSNs, a characteristic of the many-to-one (convergecast) traffic patterns. In this paper, we propose HYbrid Multi-hop routiNg (HYMN) algorithm, which is a hybrid of the two contemporary multi-hop routing algorithm architectures, namely, flat multi-hop routing that utilizes efficient transmission distances, and hierarchical multi-hop routing algorithms that capitalizes on data aggregation. We provide rigorous mathematical analysis for HYMN–optimize it and model its power consumption. In addition, through extensive simulations, we demonstrate the effective performance of HYMN in terms of superior connectivity.**

I. Introduction

Recent developments of wireless communications and nanotechnology coupled with their low costs have accelerated the spread of Wireless Sensor Networks (WSNs) [1]–[5], in which wireless-transmission capable sensor-equipped nodes are deployed in great numbers to collect information concerning areas of interest. They are ideal for a variety of applications, ranging from environmental (e.g., temperature readings) to military uses (e.g., adversary movement).

This work focuses on single sink based WSNs, in which a WSN is composed of a number of sensor nodes associated with a single sink node. The primary role of sensor nodes is to gather data of importance from its surroundings. Also, owing to the infrastructureless operation of WSNs, the sensor nodes assume the packet-forwarding role by relaying transmissions from other sensor nodes. The sink node assumes the role of a network gateway, through which data are gathered from sensor nodes, and where from users can extract the data from the WSN.

Sensor nodes are powered by batteries. Since a battery has finite energy, replacing a large number of batteries is impractical. Hence, power-efficient technologies are essential for WSNs. Consequently, much research effort has been focused on power-aware routing to prolong the operation of WSNs. However, the sink node isolation problem, defined as the isolation of the sink node as a result of the energy starvation of nodes which are close-by the sink, has not received sufficient treatment.

The design assumptions of WSNs have a great effect on the severity of the sink node isolation problem. To date, the state-of-art research on power-aware routing designed to mitigate the sink node isolation problem at the expense of deployment costs of WSNs. Therefore, in this work, we consider a WSN design that is practical, and low cost. We propose HYbrid Multi-hop routiNg (HYMN) to mitigate the impact of sink node isolation. To our best knowledge, this is the first design that considers a hybrid multi-hop routing architecture[1]. We rigorously analyze HYMN via mathematical modeling, and show its superiority via extensive computer simulations. HYMN can applied to a variety of WSN applications such as environmental monitoring, where data about the environment are gathered.

The remainder of this paper is organized in the following manner. We give an extensive literature review in Section II. Section III presents a taxonomy of contemporary WSN multi-hop routing algorithm architectures. In Section IV, we present HYMN, along with a rigorous analysis of its power consumption characteristics via mathematical modeling. Section V depicts the criteria of HYMN to achieve optimal performance in terms of minimum power consumption with respect to its hybrid boundary. We continue our evaluation of HYMN in Section VI with computer simulations, and conclude this paper in Section VII.

II. Related Works

Sink node isolation is a direct consequence of energy consumption imbalance in WSN that has been referred to by several different terms such as hotspot and energy hole problems. Ammari and Das [7] indicated that this problem was first identified in [8]. To quantify the severity of this problem, researches in [9], [10] argue that by the time when the sensor nodes that are one-hop away from the sink node exhaust their energies, sensors farther away can have up to 93% of their initial energy left.

The nature of sink node isolation is dramatically affected by WSN design, which can be categorized according to mobility, number of sink nodes, node distribution, use of multi-hop transmissions, and heterogeneity. It is worth nothing that an algorithm designer can choose to adopt one or more of these design characteristics collectively. We describe the implication of each characteristic on sink node isolation.

WSNs can be categorized into mobile-WSNs and immobile-WSNs; introducing mobility increases the cost of WSN deployment, thus dramatically affecting its feasibility. Sink node isolation in immobile WSNs is extremely challenging; on the

[1]The basic idea of HYMN was first presented at GLOBECOM 2010 [6], which received the best paper award.

other hand, WSNs which utilize mobility can overcome the above stated problem. With the sink node moving, the energy consumption can be balanced over all the nodes in the WSN. Additionally, the sink node trajectory can be calculated in a fashion that allows gathering of data as long as sensor nodes are alive. The algorithm described in [11] facilitates sink mobility to gather data, but fails to take advantage of the intrinsically correlated nature of the data collected from the WSN. In comparison, the methods proposed in [7], [12] form sensor node clusters to aggregate the data collected from the network in order to limit the volume of data that need to be transmitted. Mobility can also be utilized in wireless mobile sensor networks, where the sensor nodes are mobile and can change their positions in a deterministic manner as in [13]. Mobility in this scenario can be utilized when sink node isolation occurs, by repositioning sensor nodes in such a manner as to give the sink node sufficient routes to assure connectivity to the rest of the network. In our work, we consider the case where the sink and sensor nodes are immobile.

WSNs are classifiable according to the number of sinks in the WSN. We consider the case where the WSN is single-sinked, which is much more cost effective than a multiple-sinked WSN. Mutliple-sinked WSNs have much greater resiliency to sink node isolation. These designs partition the WSN into multiple smaller segments, effectively distributing the relay load across multiple sinks, and thus resulting into more uniform energy consumption traffic patterns in the WSN. References [14]–[16] show examples of such designs. Furthermore in [14], the multiple sinks are mobile and thus result in an additional decrease in total energy consumption of the WSN.

Wu *et al.* [17] argued that unbalanced energy depletion is unavoidable in a single sink-based WSN with many-to-one communications and uniform node distribution. Nevertheless, with a nonuniform node distribution, sink node isolation can be avoided for a longer period. Since the traffic load that sensor node incurs increases as its position gets closer to the sink node, increasing sensor node density in areas that are closer to that sink node helps mitigate sink node isolation. This design renders wasteful utility of sensor nodes because areas with a high number of sensor nodes are over monitored, thus resulting in large redundancy in traffic flow. Hence, we focus on the WSNs with uniform node distribution.

The transmission strategy in WSNs can be single-hop or multi-hop. Researches in [18], [19] demonstrate examples of WSNs with sensor nodes having the ability to vary their transmission power to send data directly to the sink in a single-hop fashion rather than using a multi-hop transmission scheme. Since using sink-direct single-hop transmission wastes the transmitting node's energy, research in this direction considers the balance between single-hop and multi-hop transmission for sensor nodes. It is impractical to improvise all nodes with the transmission power to reach the sink node directly (i.e., one-hop); the size of WSN is then limited by the one-hop transmission range of the sensor nodes, and the power consumption is likely to be inefficient. Furthermore, the work in [18] argues that balancing energy consumption via sink-direct transmission leads to inefficiencies in total energy power consumption. Thus, we consider multi-hop transmission WSN.

WSN can be heterogeneous or homogeneous. Heterogeneous WSNs [20]–[22] are a mix of normal sensor nodes and special sensor nodes. Special sensor nodes are better provisioned, in terms of power capacity, processing power, and transmission distance, and thus, heterogeneous WSNs are well equipped to mitigate the sink node isolation. Soro and Heinzelman [20] suggested deploying a group of highly provisioned sensor nodes(cluster heads), which are deterministically placed and can change their positions; these nodes act as cluster heads of groups of regular sensor nodes. The better provisioned cluster head nodes handle inter-cluster communication and change their positions to optimize power consumption. Perillo *et al.* [21] analyzed the cost trade-off of deploying a heterogeneous WSN. Mhatre *et al.* [22] considered the issue of optimizing the appropriate densities of special and normal sensor nodes to avoid sink node isolation for a guaranteed number of rounds. Heterogeneous WSNs normally incur higher deployment costs than homogeneous WSNs, and hence we opt for the latter for their feasibility.

In summary, WSNs considered in this work are homogeneously composed of normal nodes, single-sinked, immobile, and incorporated with multi-hop transmission schemes. These assumptions are practical and meet low-cost deployment constraints. To cope with these constraints, we propose HYbrid Multi-hop routiNg (HYMN) that aims to mitigate the impact of sink node isolation. Additionally, HYMN can be adopted to fit into any of the design assumptions stated above.

III. Power-aware multi-hop routing algorithms for wireless sensor networks

Routing is the process of selecting a path from a set of available paths based on some desired criteria. Intuitively, in order for the routing algorithm to maximize the WSN's network lifetime, the path that achieves minimum power consumption should be selected. Many multi-hop routing algorithms have been proposed [23]–[26]. These can be widely classified into flat multi-hop routing algorithms and hierarchical multi-hop routing algorithms, respectively.

A. Flat multi-hop routing algorithms

Flat multi-hop routing algorithms aim to select paths that minimize the total power consumption used for sending data from individual senor nodes to the sink node. Each node is able to establish communication with sensor nodes that lie within its maximum transmission range, and the individual link utilization differs depending on which routing algorithm is applied. For example, the authors in [27], [28] have proposed algorithms aiming to minimize the total power consumption while routing data from individual sensor nodes to the sink node. According to [10], [28]–[30], the following equations quantify link costs between each pair of nodes.

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

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

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

Here, the energy cost of transmitting a single unit of data from node i to node j, $linkcost(i,j)$, is attributed to two components, cost on the transmitting node $e_s(i)$ and the cost on the receiving node $e_r(j)$. Also, $e_s(i)$ is proportional to the displacement, $d_{i,j}$, between the transmitting node i and receiving node j. ϕ is the path loss exponent dependent on the wireless fading environment, its value is usually from 2 to 4, and it is 2 for short distances and 4 for long distances. The term ϵ_1 is a constant specific to a specific wireless system. ϵ_2 is the electronics energy, characterized by factors such as digital coding, modulation, filtering, and spreading of the signal. The term $e_r(j)$ is a constant equal to ϵ_3, which is a characteristic quantity dependent on the receiving node's receiving circuit. If the path, where the summation of all link costs is the minimum, is used to relay data to the sink, the total power consumed by the WSN is minimized, in effect extending the lifetime of the network.

Although the algorithm described above selects the path with the minimum power consumption, the power consumption is not uniform and overburdens certain nodes, thus leading to their quick battery depletion. This problem can be alleviated by redefining the $linkcost$ as:

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

As shown above, dividing $linkcost(i,j)$ over the residual energy of the transmitting node E_i decreases the probability of the node being chosen, thus enabling more uniform energy consumption patterns over all nodes and at the same time minimizing the total power consumption of the WSN . For example, Toh [29] selected n to be 2. Besides, the previously mentioned algorithms such as zP_{min} [30] and max–min T [31]–[34] have also been proposed.

B. Hierarchical multi-hop routing algorithms

Although flat multi-hop routing algorithms enable routing of data in a fashion that minimizes the power consumption of the WSN, they fail to exploit the data aggregation opportunities by virtue of data collected from the WSN. In many WSN applications with the relatively high node density, the data collected by individual nodes are highly redundant, thus making data aggregation a very attractive scheme in WSNs. Hierarchical multi-hop routing algorithms aim to capitalize on the highly-correlated nature of WSN's collected data. We describe the operation of the most notable example of hierarchical multi-hop routing algorithms, dubbed Low-Energy Adaptive Clustering Hierarchy (LEACH) [35], for illustrative purposes. In LEACH, nodes are organized in a two-level hierarchy, where their roles differ according to which level they belong to. That is, a node can be a Cluster Head (CH) or a Cluster Member (CM), and these roles are changeable in a unit of time referred to as a round. At the commencement of each round, some nodes take the role of CH according to a specific probability, and the rest of the nodes assume the CM role. Each CM joins a CH, and a cluster is formed out of a single CH and a number of CMs. Each CH collects data from its respective CMs, then aggregates them with its own sensed data, and transmits them directly in a single-hope fashion to the sink node.

Since CHs in LEACH transmit directly to the sink node and they are relatively fewer in number than the entire number of nodes in the network, the single-hop CH-to-sink transmission tends to become inefficient, thus resulting in rapid battery depletion in the CHs. To increase the efficiency of CH-to-sink transmission, multi-hop variants of LEACH [36] have been proposed, aiming to mitigate this problem by using multi-hop transmission between CHs and the sink node.

While CHs are chosen randomly in LEACH, modifying the scheme on selecting CHs can decrease power consumption. For example, HEED [37] gives nodes with a larger number of links a higher probability of becoming a CH, thus decreasing the communication distances between the CH and its CMs, and resulting in reduction of power consumption within each cluster. PEACH [38] gives nodes with higher residual power a higher probability to become a CH, thereby improving fairness of power consumption among nodes.

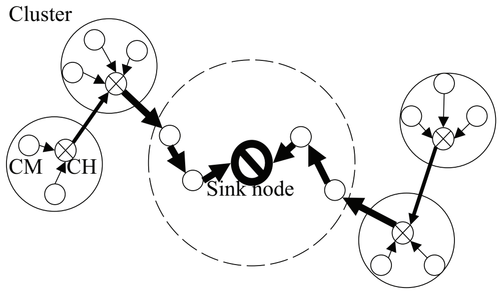
Owing to the relatively small number of nodes used to relay data, the transmission distance tends to be large, thus resulting in low-efficiency transmissions. Yet, hierarchical multi-hop routing algorithms are well suited for this scenario because of their ability to capitalize on the intrinsically correlated nature of data in the WSN.

C. Sink node isolation in WSNs

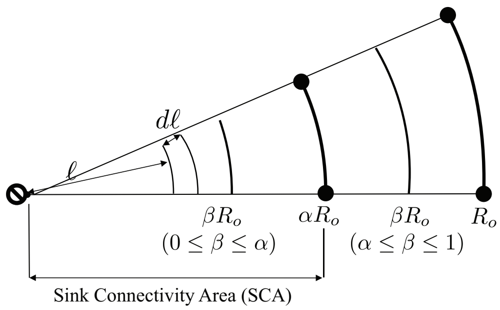
Herein, we introduce a taxonomy of WSN structure from the sink node's standpoint, and we show the importance of some specific nodes. In wireless multi-hop networks, only the nodes that lie within the circumference of the maximum transmission range of the sink node can reach the sink node via single-hop transmissions, and we refer to this area as the Sink Connectivity Area (SCA). Nodes that lie in the SCA also assist nodes that lie outside the circumference of the maximum transmission range of the sink node with connectivity to the sink node by relaying their transmitted data. Intuitively, owing to the many-to-one (convergecast) traffic patterns in WSNs, the volume of data relayed per node is proportional to how close the node is to the sink node, with nodes positioned close to the sink relaying more data, thus in effect shortening their lifetime. In general, SCA nodes have shorter lifetimes as compared to non-SCA nodes. When all SCA nodes die, the sink node becomes completely isolated from the rest of the network. In other words, to accurately quantify the lifetime of the WSN, the sink node isolation problem should be taken into consideration. In this work, we propose HYbrid Multi-hop routiNg (HYMN), as exhibited in Fig. 1(a), to mitigate the sink node isolation. We conduct rigorous mathematical analysis of HYMN, in modeling its power consumption and optimizing its hybrid boundary. Moreover, we demonstrate its superiority via rigorous simulations.

IV. HYBRID MULTI-HOP ROUTING ALGORITHM

In multi-hop wireless networks, the number of nodes in the SCA tends to be generally less than those outside the SCA, and consequently the volume of data that they sense is significantly



(a) HYbrid Multi-hop routiNg (HYMN) architecture.



(b) Considered mathematical model to optimize HYMN.

Fig. 1. HYbrid Multi-hop routiNg (HYMN).

less than the data they relay. In other words, to decrease the energy consumption of the SCA, the volume of inflow data has to be limited, and/or the energy consumption of each data relayed must be efficiently low. Our proposed algorithm HYMN, presented in Fig. 1(a), actualizes these two solutions by utilizing hierarchical multi-hop routing algorithm to restrict the influx of data coming into the SCA, and employing a flat multi-hop routing algorithm to ensure efficient data relay inside the SCA.

A. Routing outside the SCA

The power consumption of the SCA is proportional to the volume of data influx from outside the SCA that needs to be relayed by SCA nodes, and thus it is apparent that limiting this influx of data is indispensable. Applying a hierarchical multi-hop routing algorithm outside the SCA decreases energy consumption in the SCA by limiting the volume of data that the SCA nodes need to relay. It is worth noting that the inter-cluster transmission inefficiencies of hierarchical multi-hop routing algorithms only affect nodes outside the SCA.

B. Routing inside the SCA

Every unit of data inflowing into the SCA needs to be relayed by using the minimum power consumption per transmission. This objective is realizable by using a flat multi-hop routing algorithm. A flat multi-hop routing algorithm can minimize transmission distances, thus decreasing the energy consumption in the SCA.

C. Energy consumption in the SCA

In this section, we model the energy consumption of SCA by proposing the analytical model shown in Fig. 1(b) along with its parameters listed in Table I. We assume that the network is sufficiently dense in order to derive the closed form expressions. However, it should be noted that the theoretical results derived from our model are almost the same as the results of simulations unless the network is very sparse. In Fig. 1(b), the hybrid boundary, βR_o, is the location where the employed routing is changed from flat to hierarchical and vice versa. It determines the ratio between the areas where flat and hierarchical multi-hop routing algorithms are deployed. With respect to the SCA, αR_o, the hybrid boundary could exist in two locations, outside and inside the SCA.

1) The hybrid boundary is outside the SCA: When $\alpha \le \beta \le 1$, the SCA power consumption, E^{OUT}_{SCA}, can be divided to two components, as follows:

$$E^{OUT}_{SCA} = E^{OUT}_{S} + E^{OUT}_{R}, \tag{5}$$

where E^{OUT}_S and E^{OUT}_R denote the energy consumed to transfer the data sensed from inside the SCA to the sink node, and the energy consumed for relaying data inflowing to the SCA to the sink node, respectively. E^{OUT}_S is formulated as:

$$\begin{aligned} E^{OUT}_S &= \int_0^{\alpha R_o} m \times 2\ell\pi d\ell\rho \times \frac{\ell}{d_F} \times e(d_F) \\ &= \frac{2}{3}\pi m\rho \frac{e(d_F)}{d_F} R_o^3 \alpha^3, \end{aligned} \tag{6}$$

where m is message size. $2\ell\pi d\ell\rho$ represents the number of nodes within the ring of $d\ell$ width with node density ρ. ℓ/d_F is the hop count between this ring and the sink node for a flat multi-hop routing distance d_F. $e(d_F)$ is the energy consumed for sending a unit of data over a distance d_F. E^{OUT}_R is formulated by using the volume of data flow to the SCA, M, as follows.

$$\begin{aligned} E^{OUT}_R &= M \times \frac{\alpha R_o}{d_F} \times e(d_F) \\ &= \{\pi(1-\beta^2)R_o^2\rho m\gamma + \pi(\beta^2-\alpha^2)R_o^2\rho m\} \frac{\alpha R_o}{d_F} e(d_F) \\ &= \pi m\rho\ R_o^3\alpha \frac{e(d_F)}{d_F}\{\gamma + (1-\gamma)\beta^2 - \alpha^2\}, \end{aligned} \tag{7}$$

where the terms, $\pi(1-\beta^2)R_o^2\rho$ and $\pi(\beta^2-\alpha^2)R_o^2\rho$, reflect the number of nodes in hierarchical and flat multi-hop routing areas in the SCA, respectively. $\alpha R_o/d_F$ is the hop count between the hybrid boundary and the sink node. γ is the compression rate.

2) The hybrid boundary is inside the SCA: If $0 \le \beta \le \alpha$, E^{IN}_{SCA}, the energy consumption in the SCA, can be divided to four components as follows:

$$E^{IN}_{SCA} = E^F_S + E^{CM}_S + E^{CH}_S + E^{IN}_R, \tag{8}$$

where E^F_S is the energy consumption attributed to transferring the data originating from within the interior of αR_o to the sink node; E^{CM}_S quantifies the energy consumption of CMs within the SCA when they send data originated within the SCA to their respective CHs; E^{CH}_S is the energy consumed by CHs within the SCA to send their aggregated data to the sink node; and E^{IN}_R is the energy consumed to relay data flowing into the

TABLE I

Experimental settings with the associated model parameters.

Symbol	Definition	Experimental value
d_F	Average distance between nodes in flat multi-hop routing	—
d_{CH}	Average transmission distance for CHs	—
d_{CM}	Average distance between CH and CMs	—
$e(d)$	Power consumption over distance d	—
R_o	Field size	1500 [m]
α	Factor of SCA radius $0 \leq \alpha \leq 1$	—
β	Factor of hybrid boundary	—
ρ	Node density	—
δ	CH ratio $0 < \delta < 0.5$	0.2
γ	Data compression ratio $0 < \gamma \leq 1$	0.8
m	Message size	1
ϵ_1	Transmitting circuitry characteristic constant	2×10^{-7} [J/byte/m^2]
ϵ_2	Transmitting circuitry characteristic constant	2×10^{-6} [J/byte]
ϵ_3	Receiving circuitry characteristic constant	2×10^{-6} [J/byte]
—	Number of nodes	500
—	Maximum transmission range	600 [m]
—	Initial energy of each node	10 [J]

SCA to the sink node by both flat multi-hop routing nodes and CH nodes within the SCA. They are formulated as follows:

$$\begin{aligned} E_S^F &= \int_0^{\beta R_o} m \times 2\ell\pi d\ell\rho \times \frac{\ell}{d_F} \times e(d_F) \\ &= \frac{2}{3}\pi m\rho \frac{e(d_F)}{d_F} R_o^3 \beta^3. \end{aligned} \tag{9}$$

The fomulation of Eq. (9) follows that of Eq. (6).

$$E_S^{CM} = m\pi R_o^2(\alpha^2 - \beta^2)\rho(1-\delta)e(d_{CM}). \tag{10}$$

The term $\pi R_o^2(\alpha^2 - \beta^2)\rho(1-\delta)$ represents the number of CMs in the SCA.

$$\begin{aligned} E_S^{CH} &= \int_{\beta R_o}^{\alpha R_o} m\gamma \times 2\ell\pi d\ell\rho \times \\ &\quad \left\{ \frac{(\ell - \beta R_o)}{d_{CH}} e(d_{CH}) + \frac{\beta R_o}{d_F} e(d_F) \right\} \\ &= \frac{1}{3}\pi m\rho\gamma R_o^3 (\alpha - \beta) \times \\ &\quad \left\{ (2\alpha + \beta)(\alpha - \beta)\frac{e(d_{CH})}{d_{CH}} + 3\beta(\alpha + \beta)\frac{e(d_F)}{d_F} \right\}, \end{aligned} \tag{11}$$

where the terms, $(\ell - \beta R_o)/d_{CH}$ and $\beta R_o/d_F$, are the hop counts in hierarchical and in flat multi-hop routing areas, respectively.

$$E_R^{IN} = m\gamma\pi R_o^3(1-\alpha^2)\rho \times \left\{ (\alpha - \beta)\frac{d_{CH}}{e(d_{CH})} + \beta R_o \frac{d_F}{e(d_F)} \right\}, \tag{12}$$

where the terms, $(\alpha - \beta)R_o/d_{CH}$ and $\beta R_o/d_F$, are the hop counts of CHs in the hierarchical routing and the number of nodes in flat routing areas of the SCA, respectively.

V. Optimal hybrid boundary in HYMN

In this section, by utilizing the model developed in the previous section, we investigate the behavior of HYMN with respect to the SCA, β, its effect on energy consumption in the SCA, E_{SCA}, and its behavior with respect to environmental and deployment parameters, and subsequently determine the optimal hybrid boundary.

A. Optimal hybrid boundary behavior

There is a strong relationship between SCA and hybrid boundary. The hybrid boundary may exist inside or outside the SCA, as discussed below.

1) The hybrid boundary is outside the SCA: If the hybrid boundary, β, is outside the SCA, the energy consumption can be calculated from Eq. (5), and apparently from Eq. (7), E_R is a monotonic increasing function of β; thus, to minimize the power consumption of the SCA, the hybrid boundary should lie within the SCA, i.e., $0 < \beta \leq \alpha$. This result can be derived from intuition because in order to minimize the power consumption attributed to E_R^{OUT}, hierarchical multi-hop routing must be applied to all non-SCA nodes. Also, from this result, we conclude that HYMN cannot become purely composed of flat multi-hop routing.

2) The hybrid boundary is inside the SCA: Taking a closer look at $E_S^F, E_S^{CM}, E_S^{CH}, E_R^{IN}$ reveals that, E_{SCA}^{IN}, is a polynomial function of degree three, as shown below,

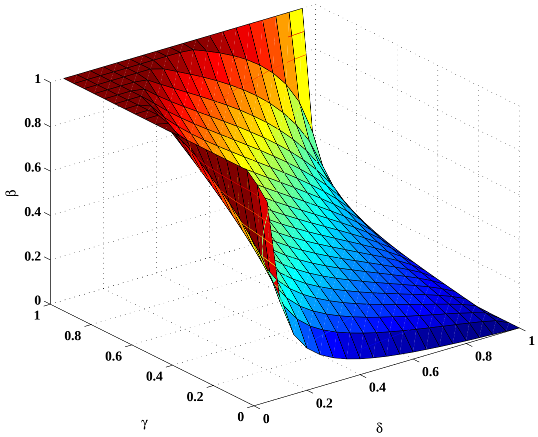
$$\begin{aligned} E_{SCA}^{IN} &= E_S^F + E_S^{CM} + E_S^{CH} + E_R^{IN} \\ &= A_1\beta^3 + A_2\beta^2 + A_3\beta + A_4. \end{aligned} \tag{13}$$

The coefficients of the above function are signed as $A_1 > 0$, $A_2 < 0$, $A_3 < 0$, and $A_4 > 0$. Applying the first derivative test can reveal information about the function's behavior, and thus

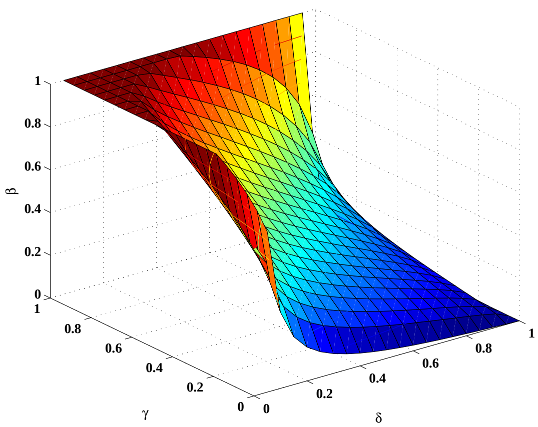
$$(E^{IN})' = 3A_1\beta^2 + 2A_2\beta + A_3. \tag{14}$$

If β is 0, i.e., the hybrid boundary coincides with the sink, and only hierarchical multi-hop routing is used, the above equation becomes

$$(E_{\beta=0}^{IN})' = A_3 < 0. \tag{15}$$

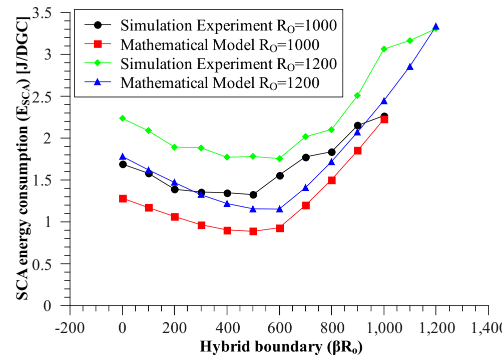


(a) Optimal hybrid boundary (βR_o) for ($R_o = 1000m$).

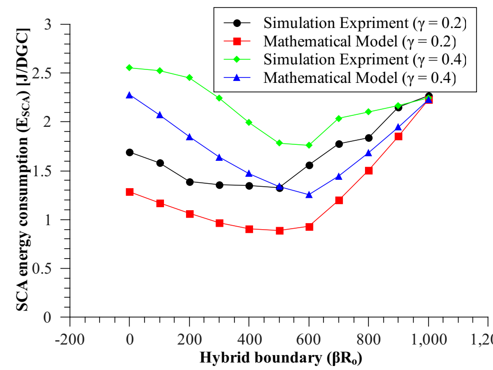


(b) Optimal hybrid boundary (βR_o) for ($R_o = 1200m$).

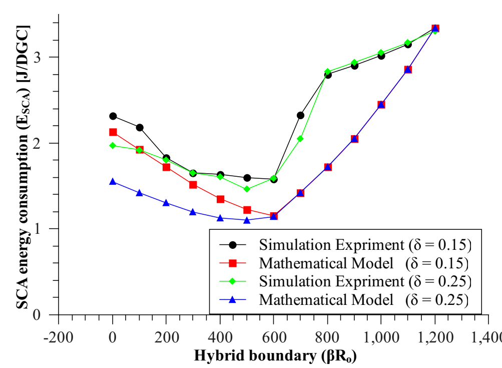
Fig. 2. Optimal hybrid boundary (R_o) for different values of R_o.



(a) Effect of field size (R_o) on optimal hybrid boundary.



(b) Effect of compression rate (γ) on optimal hybrid boundary.



(c) Effect of CH ratio (δ) on optimal hybrid boundary.

Fig. 3. Characteristics of optimal hybrid boundary.

This indicates that the function has a negative gradient, entailing that the energy consumption will decrease as the distance between the hybrid boundary and the sink increases. Furthermore, the discriminant of Eq. (16),

$$4A_2^2 - 12A_1A_3 > 0, \tag{16}$$

dictates two distinct real roots, which are the critical points of Eq. (16). We conclude that they include the point that yields the minimum of Eq. (13), and thus optimizes HYMN[2].

B. Quantifying energy consumption in the SCA

To further investigate the optimal location of the hybrid boundary, we derive a mathematical expression to quantify the power consumption in the SCA, i.e., quantifying Eq. (5) and Eq. (13). First, we derive the expected statistical values of d_F, d_{CH}, and d_{CM} defined in Tabel I. d_F, d_{CH}, and d_{CM} are related to the shape of the cluster. For example, when the shape of a cluster is predetermined, researchers have calculated these values for clusters with square [39], rhombus [40], hexagon [41], and circle [42] shapes. Alternatively, when the cluster shape is not imposed, and is allowed to follow the distributed positioning of CHs, the cluster shapes follow a Voroni diagram. The latter approach is adopted in this work for its generality. For the latter case, one can derive d_F, which represents the average distance between two nodes in an area where flat multi-hop routing algorithm is applied, as follows:

$$\pi d_F^2 \rho = 2$$
$$d_F = \sqrt{\frac{2}{\pi\rho}}. \tag{17}$$

[2]The conditions for the hybrid boundary to enter into the SCA are considered in the Appendix.

Similarly, the average distance between two CHs, d_{CH}, can be derived by following Eq. (17),

$$\pi d_{CH}^2 \rho\delta = 2$$
$$d_{CH} = \sqrt{\frac{2}{\pi\rho\delta}}. \tag{18}$$

The average distance between CMs and their respective CH, d_{CM}, i.e., the average radius of one cluster, can be derived as follows:

$$\pi d_{CM}^2 \rho\delta = 1$$
$$d_{CM} = \sqrt{\frac{1}{\pi\rho\delta}}. \tag{19}$$

Secondly, since $\epsilon_1 \gg \epsilon_2$, from Eq. (2), and by setting ϕ equal to the common value of two [8], [21], one can make the following approximation,

$$\frac{e(d)}{d} \cong \epsilon_1 d. \tag{20}$$

Energy consumption of the SCA in the case that the hybrid boundary is inside the SCA, E^{IN}, expressed in Eq. (13) as a polynomial function of β, can be rewritten by substituting Eqs. (17)-(20) into the variables A_1, A_2, A_3, A_4 as follows:

$$\begin{aligned} A_1 &= \frac{1}{3}\pi m\rho R_o^3\left\{\gamma\epsilon_1 d_{CH} + (2-3\gamma)\epsilon_1 d_F\right\} \\ &\cong \frac{1}{3}\sqrt{2\pi} m R_o^3 \sqrt{\rho}\epsilon_1 \left\{2+\gamma(\frac{1}{\sqrt{\delta}}-3)\right\} \end{aligned} \tag{21}$$

$$\begin{aligned} A_2 &= -\pi m\rho R_o^2(1-\delta)\epsilon_1 d_{CM}^2 \\ &\cong -mR_o^2\epsilon_1\left\{\frac{1-\delta}{\delta}\right\} \end{aligned} \tag{22}$$

$$\begin{aligned} A_3 &= -\pi m\rho\gamma R_o^3(\epsilon_1 d_{CH} - \epsilon_1 d_F) \\ &\cong -\sqrt{2\pi\rho} m\epsilon_1 R_o^3\gamma\left\{\frac{1}{\sqrt{\delta}}-1\right\} \end{aligned} \tag{23}$$

$$\begin{aligned} A_4 &= \frac{1}{3}\pi m\rho R_o^2\alpha\left\{3(1-\delta)\gamma\epsilon_1 d_{CM}^2 + \gamma R_o(3-\alpha^2)\epsilon_1 d_{CH}\right\} \\ &\cong \frac{1}{3}\sqrt{\pi} m\epsilon_1 R_o^2\alpha\sqrt{\rho}\times \\ &\left\{\frac{3}{2\sqrt{\pi\rho}}\cdot\frac{1-\delta}{\delta}\alpha + \gamma R_o(3-\alpha^2)\sqrt{\frac{2}{\delta}}\right\}. \end{aligned} \tag{24}$$

Similarly, the energy consumption of the SCA when the hybrid boundary is outside the SCA, Eq. (5), can be rewritten by using the value of d_f from Eq. (17) as follows:

$$\begin{aligned} E^{OUT} &= E_S^{OUT} + E_R^{OUT} \\ &\cong \frac{1}{3}\sqrt{2\pi} m\epsilon_1 R_o^3\sqrt{\rho}\{2\alpha^3 + 3\alpha\{\gamma + (1-\gamma)\beta^2 - \alpha^2\}\}. \end{aligned} \tag{25}$$

C. Optimal hybrid boundary

The location of the hybrid boundary can be determined by solving for β in

$$(E_{SCA}^{IN})' = 0. \tag{26}$$

Thus,

$$\beta = \frac{(\frac{1-\delta}{\delta}) \overset{+}{-} \sqrt{(\frac{1-\delta}{\delta})^2 + 2\pi\rho\gamma R_o^2(\frac{1}{\sqrt{\delta}}-1)\{2+\gamma(\frac{1}{\sqrt{\delta}}-3)\}}}{\sqrt{2\pi\rho}R_o\{2+\gamma(\frac{1}{\sqrt{\delta}}-3)\}}. \tag{27}$$

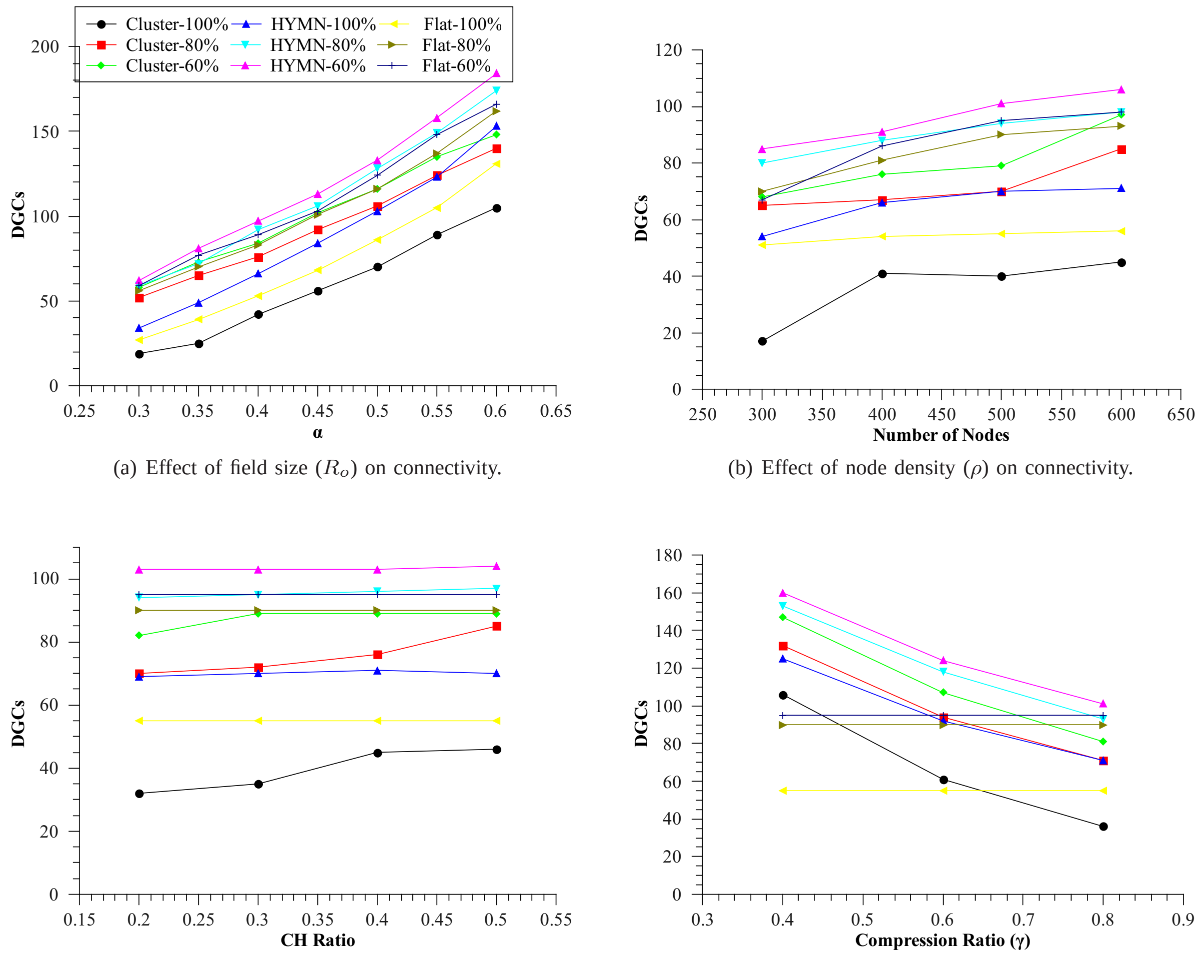
As apparent from the parameters in Eq. (27), the optimal hybrid boundary is dependent on the adopted flat and hierarchical routing algorithms, as well as environmental parameters. In the following section, we elaborate by showing how the optimal hybrid boundary behaves for different environmental parameters by using our mathematical model, and complement the analysis by simulations using Network Simulator version 2 (NS2) [43].

D. Validation

Fig. 2 represents the graph of Eq. (27), and shows the value of the optimal β for different values of γ and δ for $R_o = 1000m$ and $R_o = 1200m$; these parameters have an observable impact on the optimal hybrid boundary, unlike node density ρ. It is important to note that the maximum value of β is limited to the value of α, which is dependent on the maximum transmission range of the sensor nodes. The adopted transmission range in the remainder is set to be $600m$. The graphs demonstrate the trade-off between utilizing flat and hierarchical multi-hop routing in the SCA. As γ decreases and δ increases, β will decrease, thus increasing the area of hierarchical multi-hop routing, and consequentially, HYMN will become purely hierarchical multi-hop routing.

1) Field size: The ratio between the power consumed for transmitting data originated from within the SCA to the power consumed for relaying the data originated from outside the SCA to the sink node, is determined by two parameters, the sensing field radius, R_o, and the SCA radius, α. As this ratio decreases, so does the significance of power consumed for transmitting the data originated from within the SCA. Accordingly, the dividends gained by applying a hierarchical multi-hop routing algorithm in the SCA become insignificant. In other words, as the field size, R_o, grows, the hybrid boundary moves to coincide with the SCA's edge. Fig. 3(a) shows the energy consumption of the SCA as it changes with the hybrid boundary location, β, for different values of filed size, R_o. From the figure, it is clearly evident that the optimal hybrid boundary moves to coincide with the SCA's edge as the field size increases.

2) Compression ratio: The merit of applying hierarchal multi-hop routing algorithm is to limit the flow of data in the WSN. Its effectiveness is related to the compression ratio, γ, as this value decreases so does the volume of data flowing in the WSN; similarly, increasing the size of the hierarchical multi-hop routing area yields lower power consumption in the SCA. This phenomenon is illustrated in Fig. 3(b), which shows the change of energy consumption of the SCA with respect to the hybrid boundary, β, for different values of compression rate. The figure shows the optimal hybrid boundary moving inside the SCA as the compression rate decreases.



(a) Effect of field size (R_o) on connectivity.

(b) Effect of node density (ρ) on connectivity.

(c) Effect of CH ratio (δ) on connectivity.

(d) Effect of compression rate (γ) on connectivity.

Fig. 4. Performance evaluation.

3) CH ratio: Hierarchical multi-hop routing suffers from relatively large transmission distance. The difference in transmission distance between hierarchical multi-hop routing and flat multi-hop routing can be quantified by examining the CH ratio, δ, which represents the ratio of CH to the total number of nodes in the WSN. As the inter-cluster transmission distance increases, so does the energy consumption of the hierarchical multi-hop routing area. In effect, this pushes the optimal hybrid boundary to coincide with the SCA's edge. Fig. 3(c) illustrates the change of energy consumption of the SCA with respect to the hybrid boundary, β, for different values of the CH ratio. As shown in the graph, as the CH ratio decreases, the hybrid boundary moves away from the sink node to coincide with the SCA's edge.

VI. Performance Comparison

We investigate the performance of HYMN, as compared to the two conventional categories of multi-hop routing algorithm, flat and hierarchical. NS2 was used to execute our experiments. Sensor nodes are placed according to a random uniform distribution within a circular sensing field centered at the sink node. All the parameters in our simulation settings have been varied to examine their effect on performance. In other words, the area size and number of nodes are varied to cover a wide range of sensor node density and deployment requirements. Additionally, the CH ratio and compression rate cover a wide range of hierarchical multi-hop routing characteristics. Table I lists the configuration of the communication circuitry characteristic parameters, which are set according to the values reported by the works in [29], [35]; unless it is stated otherwise, the values in the table reflect the common simulation environment. Since the maximum transmission range of the nodes is 600m, the SCA is also a circular area with a radius of 600m having its center at the sink node. We assume that the nodes are distributed without large deviation in node density, i.e., the number of nodes in the SCA does not deviate much to accurately measure the lifetime in our conducted simulations. The simulation is set up so that all nodes in the WSN send a single packet periodically in a time frame referred to as Data Gathering Cycle (DGC). All packets need to be routed to the sink node. To illustrate the concept of HYMN, Toh's method [29] and a multi-hop variant of LEACH [36] have been employed inside and outside of the SCA, respectively. Also, these two notable multi-hop routing algorithms have been used to compare HYMN with flat and hierarchical multi-hop routing algorithms.

The performance considers the effect of deployment constraints (i.e., deployment size, R_o, and node density, ρ) and hierarchical multi-hop routing characteristic values (i.e., CH ratio, δ, and compression ratio, γ). $connectivity$, defined as,

$$Connectivity = \frac{Number\,of\,Nodes\,Connected\,to\,Sink}{Number\,of\,Nodes}, \tag{28}$$

is used as a metric for performance evaluation. The number of DGCs that the network can sustain before $connectivity$ decreases below the values of 100%, 80%, and 60% was measured and will be presented next. We adopt the notation of *algorithm type*-XX% to show how many DGCs can a routing algorithm of *algorithm type* sustain XX% of connectivity.

A. Deployment size

In Fig. 4(a), the ratio between SCA's radius and deployment size, α, is varied by changing the deployment size, R_o, and the resulting $connectivity$ is plotted. It is apparent that $connectivity$ is lost in a much more rapid manner with lower values of α. Additionally, we observe that HYMN sustains connectivity for the longest period. The reasons are that HYMN utilizes both efficient transmission distance and compression that results in better scalability as compared to the contemporary categories of multi-hop routing algorithm, and that HYMN is much more suitable for large-scale WSN deployments.

B. Node density

Fig. 4(b) demonstrates the effect of node density, ρ, on $connectivity$. As the node density is changed by modifying the number of nodes, $connectivity$ is measured and exhibited. Apparent from the figure, as ρ increases, $connectivity$ is sustained for longer periods. HYMN successfully prolongs the period of $connectivity$ for all values of node density. The lag in performance by hierarchical multi-hop routing is attributed to the relatively fewer number of nodes acting as CHs, thus resulting in longer inefficient transmission ranges in the SCA, which attribute to higher energy consumption in the SCA.

C. CH ratio

Fig. 4(c) shows the corresponding values of $connectivity$ as the CH ratio, δ, is altered. In the figure, flat multi-hop routing and HYMN are virtually unaffected by δ because δ does not affect the number of nodes in the SCA. On the other hand, the hierarchical multi-hop routing algorithm improves with higher values of δ, with HYMN sustaining its superior performance. Hierarchical multi-hop routing performance will only be able to come close to that of HYMN for impractically large values of δ. It is worth noting that δ is a characteristic value of hierarchical multi-hop routing algorithms.

D. Compression ratio

Fig. 4(d) exhibits the effect of the compression rate, γ, on $connectivity$. Intuitively, lower values of γ decrease the volume of flowing data, thus prolonging the longevity of the WSN. Flat multi-hop routing is independent of γ, and hence does not change the lifetime of the WSN. On the other hand, HYMN and hierarchical multi-hop routing algorithms benefit with lower values of γ because of the decrease of flowing data in the WSN. Evident from the figure, HYMN sustains $connectivity$ for the largest number of DGCs, and this is made possible by utilizing efficient transmission distances in the SCA that decreases the energy consumption of the SCA. Practically, the value γ is dictated by the nature of collected data, data correlation, and the employed compression algorithm.

As demonstrated in our results, HYMN successfully prolongs network lifetime by avoiding sink node isolation, thus sustaining $connectivity$ for longer periods, and surpassing the two contemporary categories of multi-hop routing algorithms.

VII. Conclusion

In this paper, we have examined the longevity of wireless sensor networks. Wireless sensor network routing algorithms are widely classified into two categories, flat multi-hop routing algorithms, which are excellent in their ability in minimizing the total power consumption of the network by efficient transmission distances, and hierarchical multi-hop routing algorithms, which decrease the volume of data flow in the network by capitalizing on the highly correlated nature of the collected data by applying data aggregation. In both categories, sink node isolation limits the longevity of the wireless sensor network. We have proposed HYMN and shown through mathematical analysis the power consumption and the conditions for optimality of HYMN. Finally, through extensive simulations, we have shown that HYMN considerably improves the longevity of wireless sensor networks. In conclusion, HYMN is promising in terms of its ability to improve the longevity of wireless sensor networks.

Appendix

A. Hybrid boundary inside the SCA

We have shown in Sec V that the optimal hybrid boundary coincides with the SCA's edge and can exist within the SCA depending on the environmental settings (e.g., monitored field size, node density) and cluster-specific parameters (e.g., CH ratio, compression rate). In this section, we further scrutinize the conditions that govern the optimal hybrid boundary location. The behavior of the optimal hybrid boundary can be understood by examining the first-oder derivative of Eq. (13) as follows,

$$\begin{aligned}
(E^{IN}_{\beta=\alpha})' &= 3A_1\alpha^2 + 2A_2\alpha + A_3 \\
&= \varphi\sqrt{2\pi}R_o\sqrt{\rho}\times \\
&\left\{2\alpha^2 + \gamma(\frac{1}{\sqrt{\delta}} - 1)(\alpha^2 - 1) - 2\gamma\alpha^2\right\} - 2\varphi\frac{1-\delta}{\delta}\alpha \\
&= \varphi\sqrt{2\pi}R_o\sqrt{\rho}\times \\
&\left\{2\alpha^2(1-\gamma) - \gamma(\frac{1}{\sqrt{\delta}} - 1)(1-\alpha^2)\right\} - 2\varphi\frac{1-\delta}{\delta}\alpha,
\end{aligned} \tag{29}$$

where $\varphi = mR_o^2\epsilon_1$. Considering the case where $\gamma = 1$, i.e., no compression, the above equation can be reformulated as follows,

$$(E^{IN}_{\beta=\alpha|\gamma=1})' = -\varphi(\frac{1}{\sqrt{\delta}} - 1)\times \left\{\sqrt{2\pi}R_o\sqrt{\rho}(1-\alpha^2) + 2(\frac{1}{\sqrt{\delta}} + 1)\right\}. \quad (30)$$

As evident from this equation, the gradient of $(E^{IN}_{\beta=\alpha|\gamma=1})'$ is negative, implying that the optimal hybrid boundary coincidences with the SCA's edge. This result is intuitive because using hierarchical multi-hop routing becomes meaningless if there is no compression. On the other hand, if $\gamma \neq 1$, i.e., there is compression, then we can derive the value of γ required for the optimal hybrid boundary to exist inside the SCA from Eq. (29) as follows,

$$(E^{IN}_{\beta=\alpha|\gamma\neq 1})' = 0$$
$$\gamma \leq \frac{2\alpha^2 - \frac{2}{\sqrt{2\pi R_o\sqrt{\rho}}}(\frac{1-\delta}{\delta})}{2\alpha^2 + (\frac{1}{\sqrt{\delta}} - 1)(1-\alpha^2)}. \quad (31)$$

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