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# Stochastic-Based Power Consumption Analysis for Data Transmission in Wireless Sensor Networks

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## Abstract

Wireless sensor networks (WSNs) provide a lot of emerging applications. They suffer from some limitations such as energy constraints and cooperative demands essential to perform sensing or data routing. The networks could be exploited more effectively if they are well managed with power consumption since all sensors are randomly deployed in sensing areas needed to be observed without battery recharge or remote control. In this work, we proposed some stochastic-based methods to calculate total power consumption for such networks. We model common arbitrary networks with different types of sensing areas, circular and square shapes, then analyze and calculate the power consumption for data transmission based on statistic problems. Almost common data collection methods are employed such as cluster-based, tree-based, neighborhood based and random routing. In each method, the total power consumption is formulated and then simulated to be verified. This paper shows promise that all the formulas could be applied not only on WSNs but also mobile sensor networks (MSNs) while the mobile sensors are considered moving at random positions.

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**Keywords:** Wireless sensor networks, data collection, clustering, random walk, routing tree, power consumption.



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## 1. Introduction

Wireless Sensor networks (WSNs) generally are intended to monitor or detect events due to each specific application [1, 2]. In the networks, sensors are often dropped and deployed randomly into sensing areas that need to be observed. The random positions of the sensors in the networks lead to difficulty of managing sensor energy that could disconnect such networks earlier than planed. The sensors connect to each other based on an appropriate transmission range or a broadcast information asking for connections due to routing algorithms [3]. The network topologies are predesigned or self-organized depending on their purposes. They are often tree-based, cluster-based or random routing algorithms that we will consider in this work for stochastic analysis.

Since all the sensor nodes in the networks are distributed randomly [4, 5], we cannot manage each sensor's energy but we can calculate the average total power consumption for the networks based on stochastic problems or their employed distribution. Based on the total expected power consumption for the network, the pre-charged batteries for sensors could be well prepared during their working time. In other words, the networks can be exploited more effectively. Since existing work does not consider power consumed for each transmission, this paper focuses on analyzing the power consumption for data transmission for sensors in the networks. We formulate the average power consumption at each hop transmission in multi-hop routing or long random distances between nodes and the BS in one-hop transmission. The total power consumption for the networks are formulated in

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different shapes of sensing areas, different assumptions and network models that provide flexible tools for calculating in WSNs.

The remainder of this paper is organized as follows. The background about power consumption for data transmission in general and related work are mentioned in Section II. Each data collection method is presented separately in each following section in which Random Walk Routing, Tree-Based Data Gathering, Cluster-Based and Neighborhood-Based Data Collection methods are addressed in Sections III, IV, V, VI, respectively. In each section, the power consumption for any data transmission in WSNs related to each data collection method is formulated, analyzed and simulated. Finally conclusions and suggestions for future work are presented in Section VII.

## 2. Background and Related work

The total power consumption for transmitting and receiving data in WSNs, denoted as $P_{Tx}$ and $P_{Rx}$ [6–8], usually calculated respectively as

$$P_{Tx} = P_{T_0} + P_A(d) \tag{1}$$

and

$$P_{Rx} = P_{R_0}, \tag{2}$$

where $P_{T_0}$ and $P_{R_0}$ are electronics consumed power, depending on some elements such as coding, modulation, signal processing. These factors do not depend on transmitting distances, denoted as $d$. Only the consumed power of the power amplifier $P_A(d)$ is a function of $d$ which we consider to formulate based on stochastic problem in this paper.

There are so many options to transmit sensory data from sensors to the BS. As mentioned in many research papers, we chose not to send directly data from every node to the BS since it costs large amount of transmitting power if the base station (BS) is far from the sensors or the sensing area. Our aims are to balance energy for the networks and to reduce power consumption in order to prolong the network lifetime. We consider the data collection below to apply our analysis of stochastic problems to formulate the total power consumption for transmitting data in such networks.

In random walk (RW) routing [9] sensors are chosen randomly to send their readings to one of their neighbors that finally to be sent to a BS after each RW. RWs do not focus on any specific position in the network and consume power at sensors quite equally. The power consumption could be shared equally through nodes. Furthermore, it is not required for sensors to know global information of the network. Some different network models are addressed in recent research that apply Compressive Sensing (CS) to save more power consumption for such networks. In [10, 11], RWs collect and add data from random sensors from a certain number of walking steps as one scalar measurement and then transmit directly data to the BS. In [12], a message generated at a given random sensor node then a random walk relays data until it reaches the BS for the first time. Papers [13, 14] mentioned that there is a mobile sink that collects data from the networks based on random walk on random geometric graphs. There are limitations for the length of RWs as cover time and mixing time which are mentioned in [9, 15]. These definitions also provide formulas for power consumption analysis depending on each specific application in WSNs.

Tree-based data gathering is also considered as energy-efficient data collection methods in WSNs. Transmitting data through short distances between intermediate nodes to the BS results low power consumption. The shortest path tree [16] provides the smallest transmission cost from sensor nodes to the BS. Minimal spanning tree [17] minimizes the total cost for transmissions in the entire tree-based network. There are many other works focus on improving the transmission cost by applying some techniques such as compressive sensing or greedy algorithms [18, 19].

Clustering algorithms have been shown to be energy efficient methods to collect data to the BS [20–25]. In [21, 22], cluster-heads (CH) are randomly chosen from sensors and the rest choose the closest CHs to join. Since the power consumption usually falls on CHs, sensors take turn to be CHs that can help balance energy. Load balancing is studied in [23] in purpose to prolong the network lifetime. In [24], the distances between a CH and non-CH sensors can be measured by a certain number of hops due to limited sensor transmission ranges. The total power consumption for the network is analyzed and minimized. HEED [25] provides an algorithm to choose CH based on sensor residual energy that also help sensors deplete energy equally.

Neighborhood based data collection has been widely used in WSNs or mobile sensor networks (MSNs). Sensor readings could be collected within each neighborhood which is created by an appropriate sensor transmission range to be sent to the BS as mentioned in [26]. In other applications, mobile sensors send their readings to their own neighbors [27, 28] for data collecting purposes or for detecting events utilizing the consensus algorithm [29, 30]. In such applications, the average values will be transmitted through the networks for a converged value and the end of a task.

In order to manage the power consumption for such data collection methods in the networks, we exploit stochastic problems and formulate total the average power consumption. Different network topologies and both common type of sensing areas, circular and square shapes are considered. We analyze and simulate each case in such networks and compare between simulation and analysis results to clarify the formulas.

## 3. Random Walk Routing

### 3.1. Network Model

We assume $N$ sensors are deployed randomly in a sensing area. Our goal is to collect sensor readings from all sensor nodes to be sent to a base-station (BS). We consider both circular and square areas in formulating our problems. The base-station (BS) could be outside or at the center of the sensing areas.

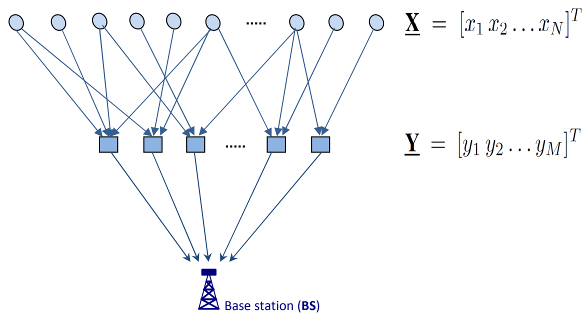


**Figure 1.** M random walks sample N sensors randomly creating M measurements to be sent to the Base-station

Based on an appropriate transmission range, denoted as $R$, all sensors are connected as a undirected graph G(V, E), where V is the set of vertexes and E is the set of edges. The number of edges can changed due to the transmission range $R$. As we increase $R$, each sensor connects to more another nodes that increases the set of edges E, or vice verse. In this model, we consider the data collection ideas of utilizing compressive sensing [31, 32] in paper [11] in which each random walk adds the readings of node it visits as one measurement, as shown in Figure 1. Each RW needs to visit through $\mathcal{L}$ nodes, also called random walk length to create one CS measurement. And $M$ measurements can be sent to the BS directly or in multi-hop transmission that will be analyzed in the following sections.

### 3.2. Communication Power Consumption Analysis

As we have the network modeled, total data transmission power consumption in the networks for sending data to the BS generally contains two elements: the consumed power for $M$ random walks and the power to send $M$ measurements to the BS directly or in multi-hop routing, that is calculated as

$$P_{total} = (P_{RW} + P_{to\,BS}). \tag{3}$$

**Analysis of $P_{RW}$.** $P_{RW}$ is the consumed energy for $M$ random walks with length $\mathcal{L}$ that can be calculated as follows

$$P_{RW} = M \times \sum_{i=1}^{\mathcal{L}} r_i^{\alpha} \tag{4}$$

$$= M\, \mathcal{L}\, \mathrm{E}[r^{\alpha}], \tag{5}$$

where $r$ is a real transmitting distance. It represents different distances between sensors while sensors forward data to each other. $\alpha$ is the path-loss exponent ($\alpha \geq 2$). It is shown that $\alpha = 2$ and $\alpha = 4$ in free space and multipath fading channels, respectively [33]. For simplicity, we chose $\alpha = 2$.

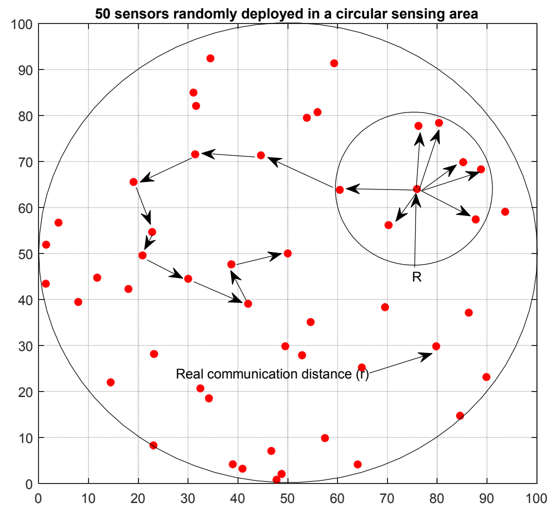


**Figure 2.** Sensor neighborhoods defined by the sensor transmission range $R$

Since sensors are uniformly distributed in a area covered by $R$ as shown in Figure 2, $r$ is also a random variable presenting the real distance between consecutive sensors along a RW (Figure 2). We can calculate the mean communication distance statistically as follows

$$\mathrm{E}[r^2] = \int\int (x^2 + y^2)\, \rho(x, y)\, dx\, dy, \tag{6}$$

where $\rho = 1/(\pi R^2)$ is the joint probability (pdf) with two random variables $x$ and $y$. We can change equation (6) into polar coordinates as

$$\mathrm{E}[r^2] = \int\int r'^2 \rho(r', \theta)\, r'\, dr'\, d\theta \tag{7}$$

$$= \frac{1}{\pi R^2} \int_{\theta=0}^{2\pi} \int_{r'=0}^{R} r'^3 dr'\, d\theta \tag{8}$$

$$= \frac{R^2}{2}. \tag{9}$$

So, the total consumed power for the network is

$$P_{RW} = M\, \mathcal{L}\, \frac{R^2}{2}. \tag{10}$$

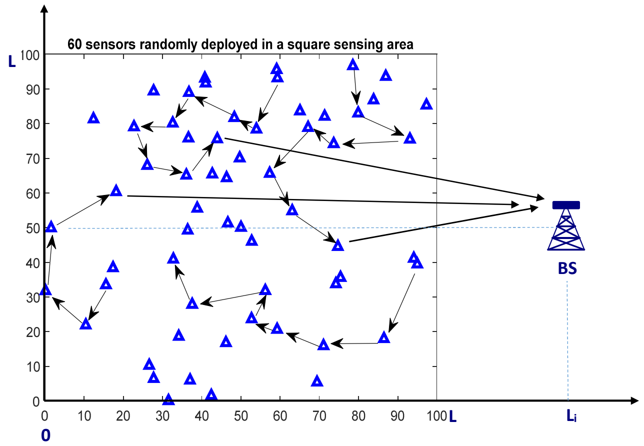


**Figure 3.** RWs collect sensory readings and send directly CS measurements to the BS at $(L_i, \frac{L}{2})$.

**Analysis of $P_{to\,BS}$.** We consider both cases to transmit the measurements to the BS, directly and in multi-hop fashion.

* ***Transmit*** $M$ ***measurements to the BS directly***: As shown in Figure 3, the BS is located at a fixed position $(L_i, \frac{L}{2})$. It means $L_i$ can be changed versus $L$ in specific cases. Since the nodes sending CS measurements to the BS are random distributed, we can calculate $P_{to\,BS}$ as

$$P_{to\,BS} = \sum_{i=1}^{M} d_i^{\alpha} = M \times \mathrm{E}[d^2], \tag{11}$$

where $d$ represents the transmitting distance between the last node of a RW and the BS that can be considered as a random variable. Since sensors and RWs are initiated randomly, we can calculate the expected square distance between RWs and BS as

$$\mathrm{E}[d^2] = \int_0^L \int_0^L [(x-L_i)^2 + (y-\frac{L}{2})^2] f(x,y)dxdy, \tag{12}$$

where $f(x,y) = \frac{1}{L^2}$ is the joint probability function (pdf). We achieve the $\mathrm{E}[d^2]$ in general case as

$$\mathrm{E}[d^2] = \frac{1}{L}[\frac{(L-L_i)^3}{3} + \frac{L_i^3}{3}] + \frac{L^2}{12}. \tag{13}$$

From Equations (3) and (13), the total power consumption for data collection in this case is

$$P_{total} = M[\mathcal{L}(\frac{R^2}{2}) + (\frac{(L-L_i)^3 + L_i^3}{3L} + \frac{L^2}{12})]. \tag{14}$$

In a specific case when the BS is at the center of the sensing area, we have $L_i = L/2$ and

$$\mathrm{E}[d^2] = \frac{L^2}{6}. \tag{15}$$

The total energy consumption in this case is

$$P_{total} = M[\mathcal{L}(\frac{R^2}{2}) + \frac{L^2}{6}]. \tag{16}$$

* ***Transmit the measurements to the BS in multi-hop***: $P_{to\,BS}$ is calculated after we have the tree-based multi-hop routing formed. Since we use multi-hop transmission not directly transmit data from RWs to the BS, so we need to formulate this consumed power as follows

$$P_{toBS} = \sum_{i=1}^{M} NoH(i) \times R^2, \tag{17}$$

where $R^2$ can be considered as the power consumption spending on each hop to relay one sensor reading.

In [34], Chandler calculated the average number of relay hops in randomly located radio network. Based on the idea, equation (17) can be written as

$$P_{toBS} = NoH_{ave} \times R^2 \times M, \tag{18}$$

where $NoH_{ave}$ represents average number of hops calculated as $\mathrm{E}[n]$ in [34]. This average number of hops is calculated based on stochastic problems. It is possible to evaluate the number since we have a connection between a random node and the BS.

The number of sensors exist in an area, called "A", follows Poisson distribution with the mean value $\lambda = \frac{N_c}{\pi R_0^2} \times A$. The probability of being able to make a connection between a random node and the BS is

$$P(\#of\,nodes \geq 1) = 1 - P(\#of\,nodes = 0) \tag{19}$$

$$= 1 - e^{-\frac{N}{\pi R_0^2} \times A}, \tag{20}$$

where $A = 2R(2\theta - sin\theta cos\theta)$ and $\theta = cos^{-1}(x/2R)$.

All sensor nodes are supposed to be deployed randomly in the sensing area. The distance between any sensor and the BS denoted as $x$ can be considered as a random variable. The probability that could make a connection at distance $x$ using $NoH$ or less hops is denoted by $P_{NoH}(x)$. As shown in [34], the expectation of the hops in a random network can be calculated as follows.

$$\mathrm{E}[NoH] = \sum_{NoH=1}^{max(NoH)} n[P_{NoH}(x) - P_{NoH-1}(x)]/P_{max(NoH)}(x) \tag{21}$$

$$= max(NoH) - \sum_{NoH=1}^{max(NoH)-1} \frac{P_{NoH}(x)}{P_{max(NoH)}(x)}, \tag{22}$$

where $max(NoH)$ is the maximum number of hops allowed. Finally, we obtain the energy consumption for RWs relaying $M$ measurements to the BS formulated as

$$P_{toBS} = \left\{ NoH_{max} - \sum_{NoH=1}^{NoH_{max}-1} \frac{P_{NoH}(x)}{P_{NoH_{max}}(x)} \right\} R^2 M. \tag{23}$$

### 3.3. Simulation Results

We consider a sensor network with 500 sensors. The sensors are uniformly randomly distributed in a square sensing area with a dimension $L \times L$ (L = 100). We also consider a circular sensing area with radius $R_0 = 50$. We also consider many different positions for the BS and compare the analysis and simulation results for accuracy checking purposes. As shown in Figure 4, the average direct distance between all sensors and the BS, mentioned in Equations (13) and (15), are calculated quite precisely while the BS at different positions from the sensing area ($L_i$ is from $1L$ to $4L$).

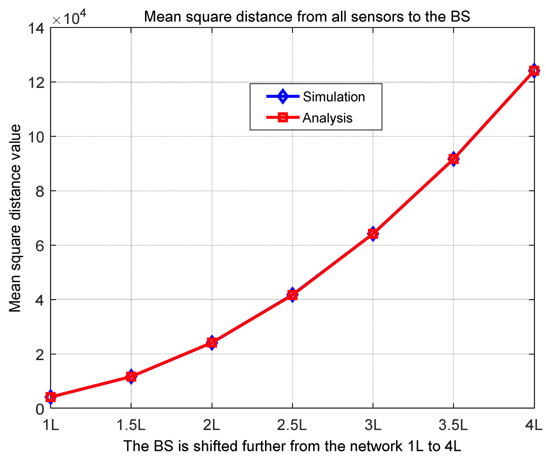


**Figure 4.** Average square distance ($E[d_{toBS}^2]$) between all random walks and the BS at different positions $L_i \geq 1L$ up to $L_i = 4L$

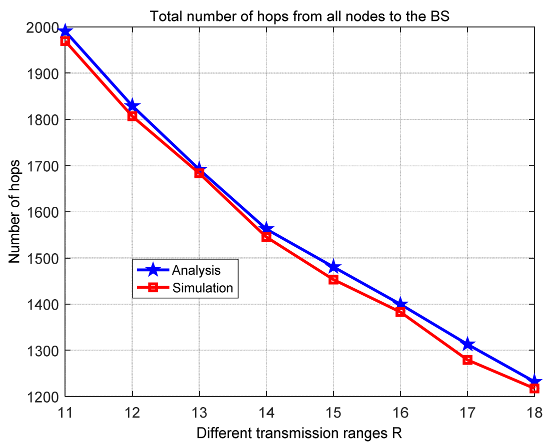


**Figure 5.** Calculation of total number of hops from all sensors to the Base-Station when the transmission range $R$ is increased from 11 to 18 [units]

In Figure 5, sensor transmission range is chosen with different values from 11 to 18 (units) to calculate the total number of hops from all sensor nodes on the relaying tree to the BS. This figure supports Equation (22) with high accuracy and also shows that the total number of hops reduces when the sensor transmission range increases.

## 4. Tree-Based Data Gathering

### 4.1. Network Model

We assume to have $N$ sensors deployed randomly in a circular sensing area with radius $R_0 = 50$. As shown in Figure 6, there are 500 sensors connected as a tree with the BS at the center of the sensing area. The tree is formed by the greedy algorithm as mentioned in [35]. The data collection in this case is that we need to collect a the sensory data to the BS.

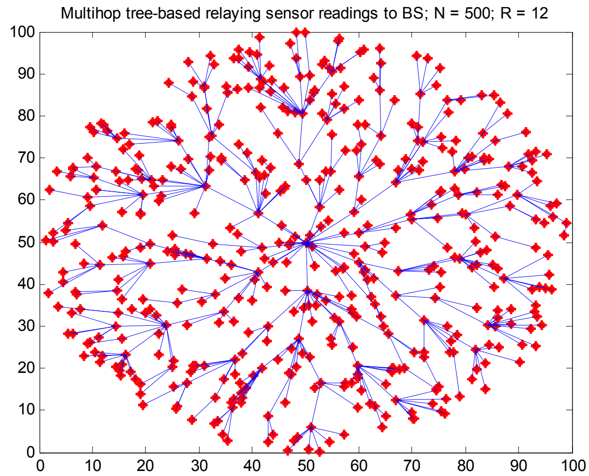


**Figure 6.** A random network with 500 sensors distributed in a circular sensing area with the radius $R_0 = 50$

### 4.2. Communication Power Consumption Analysis

Since all sensors are randomly deployed in a sensing area, we assume that we need all sensory data gathered at the base-station (BS) at the center of the sensing area. Sensor readings are transmitted through intermediate nodes to the BS based on the tree formed by a chosen routing algorithm. The total power consumption can be calculated as follows

$$P_{total} = R^2 \times \sum_{i=1}^{N} NoH(i), \tag{24}$$

where, $N$ is the total number of nodes from the network. In [34], Chandler calculated the *average* number of relay hops in randomly located radio networks. Based on this, (24) is given by

$$P_{total} = NoH_{ave} \times R^2 \times N, \tag{25}$$

where $NoH_{ave}$ is the average number of hops mentioned in [34] and calculated in Equation 22.

Finally, we obtain the total power consumption for collecting $N$ readings to the BS formulated as

$$P_{total} = N \left\{ NoH_{max} - \sum_{n=1}^{NoH_{max}-1} \frac{P_n(x)}{P_{NoH_{max}}(x)} \right\} R^2. \quad (26)$$

## 4.3. Simulation Results

In this section in order to evaluate the equations, we deploy different number of sensors in a circular sensing area with radius $R_0 = 50$ and the BS is at the center of the area. We use a fixed sensor transmission range $R = 8$ which satisfies the network is connected.

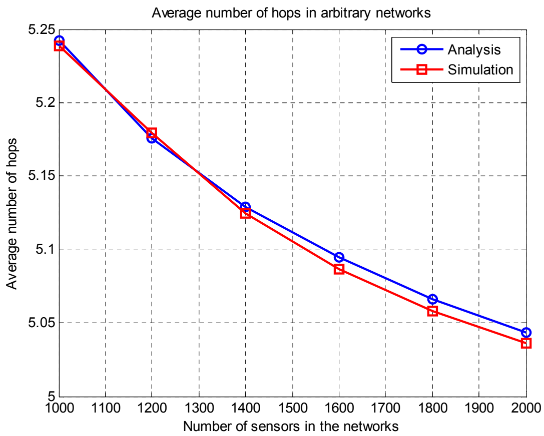


**Figure 7.** Average number of hops in circular random networks with different number of sensors, transmission range R = 8 when the BS at the center of the sensing area

Figure 7 shows the total number of hops calculated from Equation 22 and from our arbitrary networks with different number of sensors. Since the network has more nodes, each sensor has more options to choose the shortest path to the BS. So, the average number of hops is reduced in this case.

Figure 8 shows the total power consumption calculated based on Equation 26. All sensor readings are sent to the BS in multi-hop routing. The analysis and simulation results are very close to each other.

# 5. Cluster-Based Data Collection

## 5.1. Network Model

In this section, we assume to have $N$ sensors randomly distributed in a sensing area. We consider both circular and square shapes of the are need to be observed. We assume that a certain number of nodes ($N_c$) are randomly chosen as cluster-heads (CH). The other nodes choose the closest CH to join the cluster. We use K-means [20] and LEACH [21] in simulation to compare to our analysis results later. We consider the data collection ideas from [36, 37]. In [36], all sensor

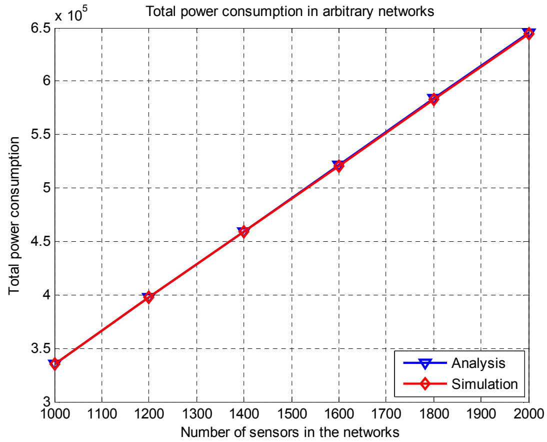


**Figure 8.** Total power consumption in random networks with different number of sensors, transmission range R = 8 when the BS at the center of the sensing area

readings from each cluster are added up together and there are only a certain number of measurements are sent to the BS directly, denoted as DCCS. In [37] the measurements are forwarded in multi-hop routing between intermediate CHs to the BS, denoted as ICCS.

## 5.2. Communication Power Consumption Analysis

We define the power consumption associated with all data transmission between non-CH nodes and the CHs that they belong to as *intra-cluster power consumption*, denoted as $P_{intra-cluster}$. The CHs can create a certain number of measurements as combinations of all received data within each cluster and finally send the CS measurements directly or in multi-hop to the BS. The corresponding power consumption is referred to as $P_{to\,BS}$. The total power consumption for all transmission in such network is calculated as

$$P_{total} = (P_{intra-cluster} + P_{to\,BS}). \quad (27)$$

We consider both sensing areas, square dimensioned $L \times L$ and circular with radius $R_0$. In each area, both methods DCCS and ICCS are formulated.

**Working on a square sensing area.** In order to analyze the network, we assume to have an uniformly distributed WSN divided into $N_c$ clusters with the same number of sensors as $N/N_c$, consisting of only one CH and $(\frac{N}{N_c} - 1)$ non-CH sensors. We achieve

$$P_{intra-cluster} = N_C(\frac{N}{N_c} - 1)\, E[r^\alpha], \quad (28)$$

where $r$ represents a distance created from a non-CH sensor to a CH that it belongs to. $\alpha$ is path loss exponent that we assume to be 2 throughout the paper. We can calculate $E[r^2]$ as follows.

$$E[r^2] = \int\int (x^2 + y^2)\,\rho(x,y)\,dx\,dy \tag{29}$$

$$= \int\int r'^2 \rho(r',\theta)\,r'\,dr'\,d\theta, \tag{30}$$

where $\rho(x,y)$ is called a node distribution. We assume each cluster area is a circle with radius $R = L/\sqrt{\pi N_c}$ and the density of the nodes is uniform throughout the cluster area, i.e. $\rho(r',\theta) = 1/(L^2/N_c)$. Finally we obtain

$$E[r^2] = \frac{1}{(L^2/N_c)} \int_{\theta=0}^{2\pi}\int_{r'=0}^{R} r'^3 dr'\,d\theta = \frac{L^2}{2\pi N_c}, \tag{31}$$

and accordingly

$$P_{intra-cluster} = (\frac{N}{N_c} - 1)\frac{L^2}{2\pi}. \tag{32}$$

As we see, the total intra-cluster power consumption is a decreasing function of the number of clusters.

* **Analysis of $P_{to\,BS}$ to forward directly the measurements to the BS (DCCS)**:
We assume the BS is located at the location $(L_i, \frac{L}{2})$ with respect to our reference point (see Figure 9). The

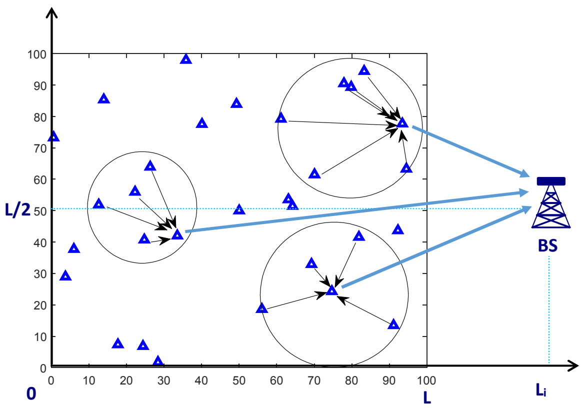


**Figure 9.** A WSN has more than three clusters with the BS outside the sensing area ($L_i > L$).

average consumed power by all CHs is given by

$$P_{to\,BS} = ME[d^2], \tag{33}$$

where $d$ is considered to be a random variable that represents a distance between a CH and the BS. It is assumed that all CHs are randomly distributed in the sensing area. The expected squared distance between all CHs and the BS is calculated in Equation 13 in Section 3.2. We finally obtain the total power consumption for the network as

$$P_{total} = (\frac{N}{N_c} - 1)\frac{L^2}{2\pi} + \frac{M}{L}[\frac{(L-L_i)^3 + L_i^3}{3}] + \frac{ML^2}{12} \tag{34}$$

We usually have two common positions for the BS, at the center of the sensing area ($L_i = L/2$) and outside the sensing area ($L_i \geq L$). For the former case, (34) is simplified as

$$P_{total} = (\frac{N}{N_c} - 1)\frac{L^2}{2\pi} + \frac{ML^2}{6}. \tag{35}$$

**Working on a circular sensing area.** We assume to have a uniformly distributed WSN divided into $N_c$ clusters with the same number of sensors as $N/N_c$, consisting of one CH and $(\frac{N}{N_c} - 1)$ non-CH nodes. We first calculate the intra-cluster power consumption as

$$P_{intra-cluster} = N_c(\frac{N}{N_c} - 1)\,E[r^2], \tag{36}$$

Similar to Equation 30, we can calculate $E[r^2]$ as follows

$$E[r^2] = \int\int r'^2 \rho(r',\theta)\,r'\,dr'\,d\theta, \tag{37}$$

where $\rho(r',\theta)$ is the node distribution as $\rho(r',\theta) = 1/(\pi R_0^2/N_c)$. We assume each cluster area is a circle with radius $R_c = R_0/\sqrt{N_c}$. Equation 37 is rewritten as

$$E[r^2] = \frac{1}{(\pi R_0^2/N_c)} \int_{\theta=0}^{2\pi}\int_{r'=0}^{R_c} r'^3 dr'\,d\theta = \frac{R_0^2}{2N_c}, \tag{38}$$

and accordingly

$$P_{intra-cluster} = (\frac{N}{N_c} - 1)\frac{R_0^2}{2}. \tag{39}$$

We can also see that the total intra-cluster consumed power is a decreasing function of the number of clusters.

Next, we need to find the power consumption to forward $M$ measurements to the BS, $P_{to\,BS}$, which is based on the distances between CHs and the BS. As mentioned, there are two methods, DCCS and ICCS which are addressed as follows.

* **Analysis of $P_{to\,BS}$ to forward directly $M$ measurements to the BS (DCCS)**:
The mean value of consumed power to transmit data from any random CH to the BS $E[d_{toBS}^2]$ can be calculated following the same idea mentioned in [11], while $d_{toBS}$ represents a real transmitting distance from any CH to the BS, as shown in Figure 10.

Since sensors are uniformly randomly distributed in the model and the CHs are also chosen randomly, we can say that $d_{toBS}$ can be consider as a random variable ($r$). And the maximum distance is the radius of the circle area $R_0$. The mean value of the square distance can be calculated as follows

$$E[d_{toBS}^2] = \int\int (x^2 + y^2)\,\rho(x,y)\,dx\,dy \tag{40}$$

$$= \int\int r^2 \rho(r,\theta)\,r\,dr\,d\theta. \tag{41}$$

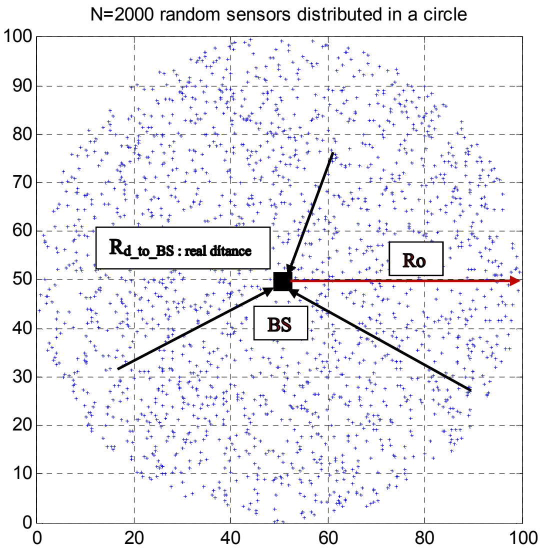


**Figure 10.** Consider real distances from CHs to the BS in a circular area arbitrary network

Assumed all sensors or CHs are uniformly distributed in the circular area with the radius $R_0$, and $\rho(x, y) = 1/(\pi R_0^2)$ is the uniform distribution of CHs (pdf), and BS is at the center of the sensing area. We obtain the average power consumption for each measurement transmitted from a random CH to the BS as

$$E[d_{toBS}^2] = \frac{1}{\pi R_0^2} \int_{\theta=0}^{2\pi} \int_{r=0}^{R_0} r^3 dr\, d\theta \tag{42}$$

$$= \frac{R_0^2}{2}. \tag{43}$$

Finally, we have the total power consumption for such networks

$$P_{total} = (\frac{N}{N_c} - 1)\frac{R_0^2}{2} + M\frac{R_0^2}{2}. \tag{44}$$

* **Analysis of $P_{toBS}$ to forward $M$ measurements through inter-cluster multi-hop (ICCS)**:
In case we apply inter-cluster multi-hop relaying data through CHs, we need the average number of hops from Equation 22 to calculate the total power consumption as

$$P_{total} = (\frac{N}{N_c} - 1)\frac{R_0^2}{2} + P_{toBS}, \tag{45}$$

where $P_{toBS}$ can be calculated as

$$P_{toBS} = M\left\{NoH_{max} - \sum_{n=1}^{NoH_{max}-1} \frac{P_n(x)}{P_{NoH_{max}}(x)}\right\} R_c^\alpha, \tag{46}$$

and $R_c$ is the transmission range for each CH to create a tree for routing data. The tree can be formed as tree-based routing, mentioned in the previous section.

## 5.3. Simulation Results

In this section we consider circular sensing area with radius $R_0 = 50$. There are 2000 sensor nodes are deployed randomly the sensing area. The network is divided into different number of clusters of $N_c = [100,\ 200,\ 300,\ 400]$ that corresponds to the CH's transmission range $R_c = [25,\ 22,\ 18,\ 14]$.

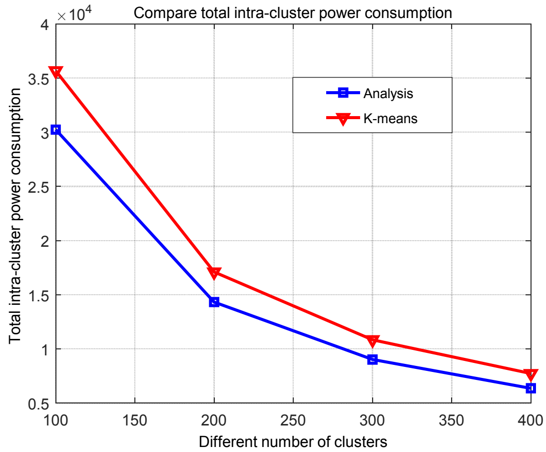


**Figure 11.** Total intra-cluster power consumption when N = 2000 sensors deployed in a circular sensing area with $R_0 = 50$; BS at the center

Figure 11 depicts the total intra-cluster power consumption ($P_{intra-cluster}$) as formulated in Equation 39. The analysis result is also compared with another network clustered by K-means. In our formula we assume to have all clusters with equal size. So, in the figure, both the power consumption values at different number of clusters are quite similar.

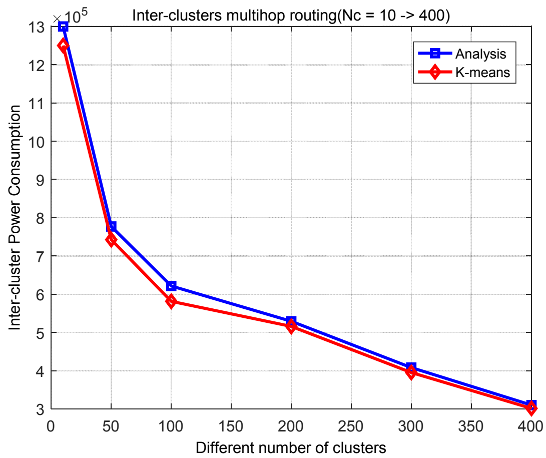


**Figure 12.** An illustration of a total inter-cluster power consumption; a WSN with 2000 sensors randomly deploying in a circular sensing area ($R_0 = 50$; BS at the center)

Figure 12 depicts the total inter-cluster power consumption ($P_{toBS}$) to forward $M$ measurements to the BS in multi-hop through intermediate CHs, as formulated in Equation 46. Our analysis result is also compared with an arbitrary network clustered by K-means clustering algorithm. All the equations are classified well when both analysis and simulation results come very close to each other.

## 6. Neighborhood-Based Data Collection

### 6.1. Network Model

We assume to have $N$ sensors are randomly distributed in a sensing area. Given an appropriate transmission range $R$, all the sensors are connected as an undirected graph G(V, E), where $V$ is the set of vertexes is always equal to $N$. $E$ is the set of edges that counts the possible communication links between the sensors depending on the value of transmission range $R$. As mentioned in [26], $M$ random sensors out of $N$ are chosen to collect sensor readings from their own neighbors' including themselves to create CS measurements. After that, these $M$ measurements are sent to the BS directly or are relayed through intermediate nodes.

### 6.2. Communication Power Consumption Analysis

The total power consumption for all data transmissions as mentioned in the network model has two main parts, the power consumed for transmission between $M$ neighborhoods denoted as $P_{nei}$ and the other one to forward $M$ measurements to the BS, denoted as $P_{to\,BS}$, as shown as bellows

$$P_{total} = (P_{nei} + P_{to\,BS}). \tag{47}$$

We assume that each neighborhood has the same number of sensors that depends on the sensor density of the network. $P_{nei}$ is calculated as

$$P_{nei} = \omega \times R^2 \times M, \tag{48}$$

where $\omega$ represents an average number of neighbors that each sensor can have. It is assumed that sensors are randomly distributed in the area. The average number of nodes can be calculated depending on the area covered by each sensor transmission range $R$ as $\frac{N}{R_0^2} \times R^2$. By analyzed, we can calculate the mean value as $\omega$ as follows.

$$\omega = (N\frac{R^2}{R_0^2} - 1). \tag{49}$$

Hence, the total consumed power for data gathering in $M$ neighborhoods is calculated as

$$P_{nei} = (N\frac{R^2}{R_0^2} - 1)R^2 M. \tag{50}$$

* Note that in a square sensing area, $\omega$ is calculated differently as

$$\omega = (N\frac{\pi R^2}{L^2} - 1). \tag{51}$$

*** Analysis of $P_{to\,BS}$ to forward directly $M$ measurements to the BS (DirectNei)**
Each chosen node after generating the measurement transmits directly it to the BS. We can calculate $P_{to\,BS}$ based on Equation 43 and finally obtain the total power consumption in this case as

$$P_{total} = (N\frac{R^2}{R_0^2} - 1)R^2 M + \frac{R_0^2}{2}M. \tag{52}$$

*** Analysis of $P_{to\,BS}$ to forward $M$ measurements in multi-hop to the BS (Multi-hopNei)**
In other case we choose to transmit data from each neighborhood to the BS through intermediate nodes by multi-hop routing, $P_{to\,BS}$ can be calculated based on Equation 22 to calculate the average number of hops from each neighborhood to the BS. Finally, the total power consumption in this case is

$$P_{total} = (N\frac{R^2}{R_0^2} - 1)R^2 M + P_{to\,BS}, \tag{53}$$

where $P_{to\,BS}$ is

$$P_{to\,BS} = M\left\{NoH_{max} - \sum_{n=1}^{NoH_{max}-1}\frac{P_n(x)}{P_{NoH_{max}}(x)}\right\}R^2. \tag{54}$$

### 6.3. Simulation Results

In this section, we consider a circular sensing area and deploy different number of sensors randomly on it. We chose a fixed a sensor transmission range $R = 9$ and guaranteed that the network is always connected. Our goal is to verify our formulas in arbitrary networks.

Figure 13 depicts the total intra-neighborhood power consumption from all $N$ sensor nodes. As we increase the number of nodes, this power consumption increases. The gap between our analysis and simulation results also increases. In analysis case, we assumed that all sensors have the same number of neighbors but in an arbitrary network, sensors close to the boundary have less neighbors than the ones in the middle of the sensing area. We can increase the transmission range to reduce the error of calculation between these two results.

We consider that each sensor uses tree-based routing tree [26] to relay the data to the BS at the center of the sensing area. Figure 14 depicts the total power for all the sensors (different numbers of sensors are deployed) send their data to the BS through the intermediate nodes to the BS.

In Figure 15 we calculate the total power consumption based on Equations (52) and (53) for both ways to transmit a certain number ($M$) of measurements to the BS. If we do not consider network latency or capacity, transmitting in multi-hop (Multi-hopNei) consumes 30 − 40% less power than transmitting directly (DirectNei) $M$ measurements to the BS.

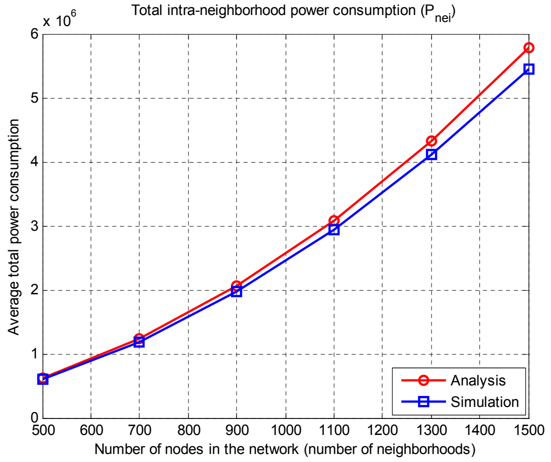


**Figure 13.** Total intra-neighborhood power consumption with different number of sensors deployed in a circular sensing area

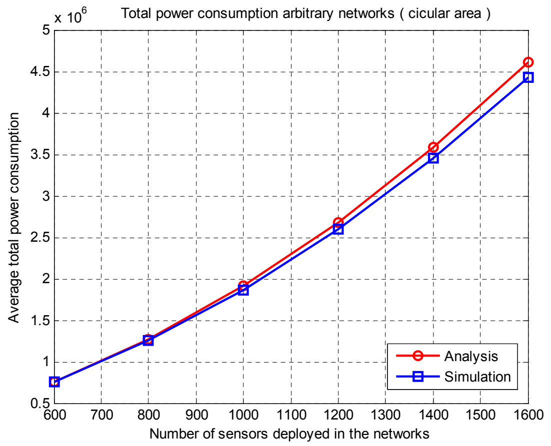


**Figure 14.** Total power consumption with different number of sensors deployed in a circular sensing area; multi-hop routing is applied to transmit data from each neighborhood to the BS at the center of the sensing area

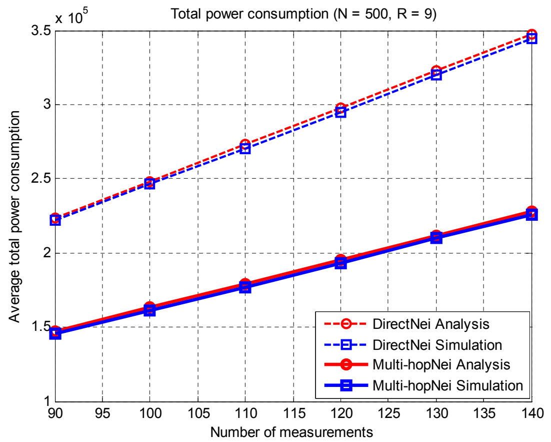


**Figure 15.** Total power consumption with different number of measurements sending to the base-station (BS) in both methods are compared; The BS is at the center of the sensing area; N = 500 sensors; transmission range $R = 9$

## 7. Conclusions

In this paper, we formulate the average power consumptions for data transmission in WSNs based on stochastic problems. Almost the common network topologies such as tree-based, random walk, neighborhood-based and cluster-based are considered. The consumed powers of power amplifiers at sensors which are function of transmitting distances are formulated as average power consumptions. All transmitting power consumptions are formulated for such network topologies. Both analysis and simulation results are addressed to compare and verify the formulas. Based on the results, some optimal cases are suggested for such networks to minimize power consumption in order to prolong the network lifetime.

In future work, we focus on different distributions of sensors deploying in sensing areas to calculate power consumption. Some general calculations could be provided for hybrid networks. Based on those ideas, either WSNs or MSNs can be managed better with longer time of operation.

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