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Research Article

Mobile Base Station and Clustering to Maximize Network Lifetime in Wireless Sensor Networks

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Using a mobile base station (BS) in a wireless sensor network can alleviate nonuniform energy consumption among sensor nodes and accommodate partitioned networks. In the work of Jerew and Liang (2009) we have proposed a novel clustering-based heuristic algorithm for finding a trajectory of the mobile BS that strikes a nontrivial tradeoff between the traffic load among sensor nodes and the tour time constraint of the mobile BS. In this paper, we first show how to choose the number of clusters to ensure there is no packet loss as the BS moves between clusters. We then provide an analytical solution to the problem in terms of the speed of the mobile BS. We also provide analytical estimates of the unavoidable packet loss as the network size increases. We finally conduct experiments by simulation to evaluate the performance of the proposed algorithm. The results show that the use of clustering in conjunction with a mobile BS for data gathering can significantly prolong network lifetime and balance energy consumption of sensor nodes.

1. Introduction

The development of wireless communication and microsensing offers a convenient way to monitor physical environments such as bushfires, ecological systems, and personal health, and it can facilitate intelligent transportation. A sensor network consists of a large number of small devices that have sensing, processing, and transmitting capabilities and that are powered by small batteries. Data gathering is one of most frequent and fundamental operations in sensor networks; the efficiency of implementing this operation to some degree determines network lifetime.

By introducing mobility to wireless sensor networks (WSNs), communication energy consumption can be reduced [1–3]. For instance, a mobile base station (BS) can roam a sensing field and gather data from sensor nodes through a short transmission range. The energy consumption of each sensor node is then reduced, since fewer relays are needed for the sensor node to relay its message to the BS [4]. However, the increased latency of data gathering when employing mobile BS represents a major performance bottleneck in WSNs, because the time a mobile BS takes to tour a large sensing field may not meet the stringent delay requirements inherent in some mission-critical real-time applications. The speed of the mobile BS is thus a fundamental design constraint: the faster the speed, the higher the manufacturing cost of the mobile BS [4, 5].

Data gathering is one of most frequent and fundamental operations in sensor networks; the efficiency of implementing this operation to some degree determines network lifetime. In a flat routing topology, sensor nodes near the BS consume much more energy than others, since they relay data packets for others. Hierarchical organisation of sensor nodes is introduced in the design of routing protocols to avoid the energy imbalances inherent in a flat routing topology [6, 7]. Sensor nodes are organised into clusters, and cluster heads relay aggregated results of data sensing within clusters via the other cluster heads to the BS. Each cluster head is responsible for coordination of its sensor nodes. The sensor nodes within a cluster transmit their sensed data to the cluster head through multihop relays.

In this paper, we consider data gathering in a mobile BS environment, subject to a specified tour delay time constraint on the mobile BS, by adopting a clustering-based approach. To reduce the energy consumption of a cluster head to forward sensing data, the mobile BS roams the sensing field and visits only the cluster heads to gather sensing data. Therefore, the distribution of the cluster heads in the entire network affects the load balance among the sensor nodes and hence the network lifetime.

Our earlier work [8] proposed a heuristic algorithm for finding a trajectory of the mobile BS consisting of cluster heads which meets the following criteria: (i) the energy consumption among the sensor nodes within any cluster is balanced, and (ii) the total traversal time of the mobile BS on the trajectory is bounded by a given value. We demonstrated by simulation in [8] that the proposed algorithm significantly increases the network lifetime. Here we extend that work by analytical calculations of the lifetime improvement. Our results make it possible to determine the lifetime improvement in different applications. In addition, the number of clusters is a key parameter in the algorithm, and here we provide an analytical method for determining the best value to use according to particular situations.

The rest of the paper is organised as follows. Section 2 reviews the related work. In Section 3, we introduce the preliminaries and path planning problem. Section 4 describes the trajectory of the mobile BS, process of cluster formation, and finding cluster heads. Section 5 estimates bounds on the number of clusters. Section 6 studies the factors that affect network lifetime, packet loss, and maximum speed of the mobile BS. In Section 7, we consider the use of a mobile BS in practical data gathering applications. In Section 8, extensive experiments by simulation are conducted to evaluate the performance of the proposed algorithm, and, finally, this paper is concluded in Section 9.

2. Related Work

The use of mobile BSs for data gathering in wireless sensor networks has been proposed for addressing a variety of different situations [1–3, 9]. In some cases the motivation is to enhance connectivity in sparse networks [10–12], in which mobile BSs are used to collect data from sensors that are only capable of local, single hop communications. Various methods of determining the BS tour to visit all nodes efficiently have been proposed [13].

Our work assumes a dense, fully connected static network, with all nodes able to participate in multihop data forwarding by sensor nodes. In this case the BS path is not directly constrained by the location of the sensors, since data can be forwarded to sensors known to be close to a predetermined BS path. Straight line paths [14, 15] have been considered, as well as a BS with an arbitrary pre-determined path [16]. The use of mobile BS allows nodes to save energy (and thus preserve network lifetime), since they do not have to forward messages all the way to the BS; however, nodes close to the BS path will consume more energy than those far away.

Ma and Yang [17] proposed a heuristic for finding the moving path of mobile BS that consists of a series of line segments, and sensor nodes closest to each line segment are selected as cluster heads. This scheme improves network lifetime. However, it may not balance the energy consumption among sensor nodes, since the position of cluster head within each cluster is not considered in cluster forming.

Luo and Hubaux [3] proposed an analytical model to find a trajectory of the mobile BS for data gathering through multi-hop relays. They represented the sensing field as continuous model and demonstrated that the BS mobility improved the sensors load balance even when the BS moves at arbitrary directions. They showed that the tour of the mobile BS that maximizes network lifetime is the perimeter of the sensing field.

Some schemes assume multiple mobile BSs, which may communicate with each other [15, 18, 19], but we confine out attention to the case of a single mobile relay. Other schemes assume that the sensor nodes can cache forwarded data [4, 20]. However, we assume a homogenous network, where the cluster head is a simple sensor with limited cache ability, since the capacity for caching will increase the complexity and energy usage of the sensor node.

Most literature mentioned assumes that the mobile BS traverses the sensing field at constant speed. In contrast, Sugihara and Gupta [21] assumed that the BS can select the path and change its speed under a predefined acceleration constraint to achieve minimum data-delivery latency and minimize the energy consumption of sensor nodes. They formulated the problem as a traveling salesman problem and schedule the travel time at each edge in the trajectory to maximize the amount of collected data. Our research assumes that the average speed of the mobile BS is constant, as changing the speed of the mobile BS leads to significantly higher manufacturing costs and power consumption.

Shi and Hou [22] theoretically studied the optimal movement of the mobile BS and routing. They transformed the movement of the BS and routing flow from time-dependent problem into a location-dependent problem. They reduced the movement of the BS to a finite set of locations and proposed an algorithm to guarantee the network lifetime to be least of $(1-\epsilon)$ the unknown maximum network lifetime, where ϵ is arbitrarily small. Liu et al. [23] considered data collection rate and network lifetime in the analysis of data gathering using mobile BS in a clustered sensor networks. They assumed that some sensor nodes (rendezvous points) cached sensing data of other nodes, and the mobile BS waits close to rendezvous point for receiving sensing data. They studied the effect of the BS speed and hence the time that the BS spends for data gathering on throughput capacity and the optimal number of clusters. However, this work does not consider data gathering delay, in contrast to our work which assumes maximum possible delay restricts the BS tour length and considers a single mobile BS.

The main contribution of this paper is an analysis of the algorithm presented in [8]. We analytically study the upper and lower bounds on the number of clusters such that there is no packet lost due to moving too fast through a cluster or interference between cluster heads. Statistical methods are used to determine the probability of finding cluster heads and of losing packets as the BS moves from one cluster to another. We then examine how the resulting network lifetime varies with node density.

Table 1: Definitions of the main symbols used throughout the paper.

Symbol	Description
D	Data gathering delay: time available for a mobile BS tour
r	Transmission range of a sensor node
L	Maximum allowable length of the mobile BS tour, $L = DV_m$
L_m	Actual length of the mobile BS tour
L_K	Length of the mobile BS tour connecting cluster centroids
V_m, $V_{\max}$	Average and maximum speed of the mobile BS, respectively
T_{rq}	Packets request time, from data request to receiving the first data packet
T_P	Packet time: average time required to transmit a data packet to the BS
T_C	Contact time
T_R	Residual contact time
T_{pks}	Total time to send data of the cluster nodes to the BS ($T_{pks} = n_K T_P$)
R	Radius of the network field
n	Network nodes
K	Number of the clusters
n_K	Number of nodes in a cluster
n_s	Number of nodes the cluster head can successfully send their data to the BS
l	Number of packet losses

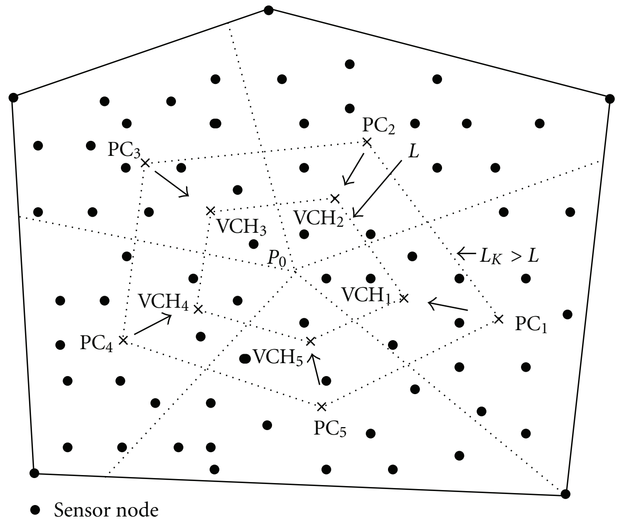


Figure 1: An illustrative example of virtual cluster heads calculation, for $K = 5$ clusters. PC_i and VCH_i, $1 \leq i \leq K$ are the locations of clusters' area centre points and virtual cluster heads, respectively. L is the length of the BS tour required, and L_K is the BS tour length connecting PC_i.

3. Preliminaries and Problem

We assume the transmission range of each sensor node is fixed and identical, and all sensor nodes have identical initial energy. The storage of a sensor node is limited, so that it cannot buffer a large volume of data. Sensor nodes are densely deployed in the sensing region (average node degree ≥ 8). Accordingly, the number of hops in a path is approximately proportional to the distance between the nodes.

The BS moves with constant velocity. Thus, there is sufficient time to establish communication and send one or more data packets during the time the BS takes to travel across the transmission range of a sensor node ($T_{rq} + T_P \ll 2r/V_m$ using notation in Table 1). Moreover, the speed of relaying a data packet by sensor is much faster than the moving speed of a mobile BS ($T_P \ll T_C$ using notation in Table 1). Thus, the total delays in data gathering can be mapped into the maximum length of a BS tour. The mobile BS replenishes its energy periodically so that there is no energy concern with the mobile BS. Finally, sensor nodes and the mobile BS are assumed to know their own physical locations via GPS or a location service in the network. Table 1 shows the main symbols used in the paper. The problem addressed in this paper is as follows.

Problem. Given a network with a mobile BS, assuming that the length of a BS tour is bounded by L, and its speed is V_m, the problem is to find a tour for the mobile BS such that the network lifetime is maximized.

4. Algorithm

We address this problem by organising sensor nodes into clusters such that all the cluster heads can be visited by the mobile BS. The location of the cluster head in its cluster is an essential factor in balancing the energy consumption of the cluster-sensor nodes and determining the length of the BS tour. The challenge in this problem is to find the optimal locations of cluster heads by jointly considering the BS tour and the network lifetime.

To determine the BS route, we first determine clusters, then identify a virtual cluster head, VCH, for each cluster, and finally identify sensor nodes which are real cluster heads. To balance energy consumption among sensor nodes, it is important to select the cluster head such that each sensor node in a cluster is within a certain number of hops from its cluster head.

The sensing field is divided into equal subareas by radial lines from the centre (centroid) of the field. All the nodes located in the same subarea form one cluster. The VCH for each cluster is located at the centroid of the cluster. Sensor nodes near to the VCH become the candidates for the cluster head if the length of the BS tour is no greater than L. Otherwise the tour length must be reduced by relocating the VCH towards the centre of the sensing field. To achieve a load balance among cluster sensor nodes, the same amount of movement is employed to each virtual cluster head. The concept of relocating VCHs is illustrated in Figure 1. Finally, sensor nodes close to VCHs are selected as the real cluster head if the length of tour is no greater than L. For details of the proposed algorithm, refer to our work in [8].

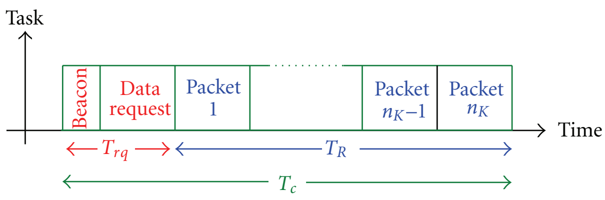


Figure 2: The mobile BS data gathering scenario.

The BS route is a smooth trajectory passing over each real cluster head. The cluster heads are the bottlenecks of energy consumption, since they have to forward the sensing data of sensor nodes within them to the mobile BS. Our technique aims for an equal number of sensors in each cluster in order to achieve load balance among the cluster heads. Other researchers use quite different criteria for forming clusters [17, 21]. Our technique balances energy consumption and data gathering time among the cluster heads.

5. Choosing the Number of Clusters

The algorithm for finding the tour of a mobile BS employs the number of clusters, K, as a system parameter. In this section, we aim to analytically study the upper and lower bounds of the number of clusters needed. The minimum number of clusters, $K_{\min}$, is determined by the maximum number of nodes that can be in a cluster before packets begin to be lost, and the maximum number of clusters, $K_{\max}$, arises from the requirement that the transmission regions of the cluster heads do not intersect.

5.1. Minimum Number of Clusters. The cluster head transmits sensing data when the mobile BS is within its transmission range. The transmission time available to the cluster head is determined by the speed of the BS, thus, there is a maximum number of packets that can be sent at that time. The network must have at least $K_{\min}$ clusters to ensure that the transmission load for each cluster head is not too high.

When the mobile BS reaches the transmission range of a cluster head, it advertises its presence by periodically broadcasting a special packet called a *beacon*. A cluster head, upon receiving the beacon, broadcasts the beacon packet, requesting that the cluster nodes send their data to the cluster head. Let the time from when the mobile BS enters the transmission range of the cluster head to when it receives the first sensing data be T_{rq} and the time taken by the mobile BS to traverse the transmission range of the cluster head be T_C. Since the mobile BS visits each cluster head, $T_C = 2r/V_m$. We assume that only one packet can be transmitted from the cluster head at a time. Thus, the residual time available for gathering cluster data is $T_R = T_C - T_{rq}$, as shown in Figure 2.

Let T_P be the average time required for the cluster head to collect and send a data packet to the mobile BS. Assume there are n_K sensor nodes in a cluster, then $T_{pks} = n_K T_P$ is the time required to collect the sensing data from that cluster. If $T_R \geq T_{pks}$, no packet loss is incurred in data gathering. However, if $T_R < T_{pks}$, then the residual time is not enough to collect all of the data packets in the cluster. The number of packets that can be successfully transmitted is $n_s = \lfloor T_R/T_P \rfloor$, where $\lfloor x \rfloor$ is the largest integer less than x. In summary, the number of packets lost is given by

$$P_{\text{loss}} = \begin{cases} 0 & T_R \geq T_{pks}, \\ n_K - n_s & T_R < T_{pks}. \end{cases} \quad (1)$$

The minimum number of clusters necessary can be found by allowing $T_R = T_{pks}$. If all clusters have the same number of nodes, we would have $n_K = \lceil n/K \rceil$, where $\lceil x \rceil$ is the largest integer greater than x. Substituting into $T_R = T_C - T_{rq}$, we find

$$K_{\min} = \left\lceil \frac{n T_P V_m}{2r - V_m T_{rq}} \right\rceil. \quad (2)$$

However, nodes are independent and identically uniformly distributed; the number of sensor nodes in each cluster can be modeled by a binomial distribution $n_K \sim B(n, 1/K)$. The probability function of the time required to collect cluster packets is given by

$$f_{T_{pks}}(t = n_K T_P) = \binom{n}{n_K} \left(\frac{1}{K}\right)^{n_K} \left(1 - \frac{1}{K}\right)^{n-n_K}, \quad (3)$$

where $t = 0, T_P, 2T_P, \ldots, nT_P$. The probability that l packets are lost is

$$f_L(l) = \begin{cases} \sum_{t=0}^{n_s T_P} f_{T_{pks}}(t) & l = 0, \\ \binom{n}{l+n_s} \left(\frac{1}{K}\right)^{l+n_s} \left(1-\frac{1}{K}\right)^{n-(l+n_s)} & l = 1, 2, \ldots, n-n_s. \end{cases} \quad (4)$$

The cumulative distribution function (CDF) is $F_L(l) = \sum_{i=0}^{l} f_L(i)$. Figure 3 shows that the CDF of the percentage of numbers of packet losses is plotted for different numbers of clusters. The network parameters are configured such that the approximate $K_{\min}$ is eight. The result shows that the probability of achieving any given threshold level of packet loss increases with the number of clusters. For instance, the probability of achieving packet loss less than 2% is 0, 0.26, and 1 for the number of clusters 4, 6, and 8, respectively.

5.2. Maximum Number of Clusters. We have shown that packet loss decreases with the increasing number of clusters due to decrease in the forwarding load for each cluster heads. However, increasing the number of clusters decreases the distance between cluster heads of adjacent clusters, so that eventually the transmission range of cluster heads overlaps, which decreases the effective contact time because transmissions by each cluster head interfere with the others when the BS is in the region where their transmission ranges overlap. Therefore, we require that the distance between cluster heads is at least $2r$.

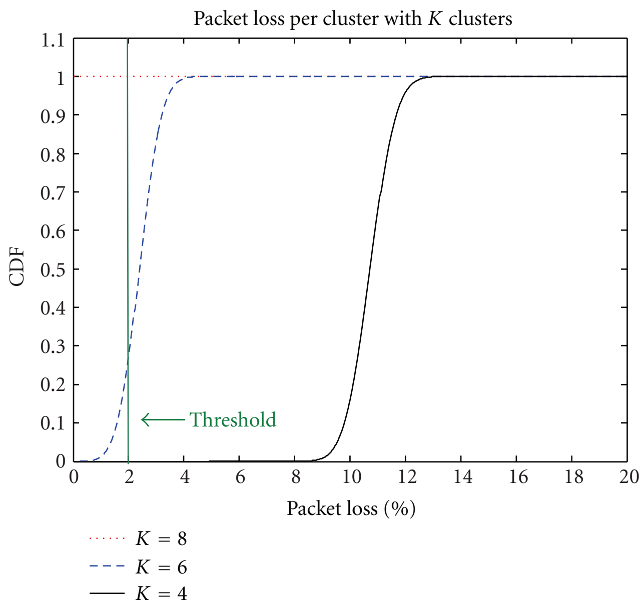


FIGURE 3: The effect of the number of clusters on the CDF of the percentage of number of packet losses. The approximate $K_{\min}$ is eight from (2), when $r = 100$ m, $V_m = 2$ m/s, $n = 3500$, $T_{rq} = 10$ ms, and $T_P = 200$ ms.

We now investigate the effect of increasing the number of clusters on the length of the BS tour and the probability of finding a real cluster head.

First, assume that the VCH is located at the centroid of the cluster indicated by a bullet in Figure 4(a). Assume the sensing field is a circle, with radius $R > 2r$ (as illustrated in Figure 4(a)), and let $\theta_K = 2\pi/K$ represent the angle between the boundaries of the cluster area. Then the distance between the VCH and the centre of the sensor field is $\ell = 2RK\sin(\pi/K)/3\pi$. Then, the length of tour segment between adjacent VCHs is $\delta = 2\ell\sin(\pi/K)$, and the length of the BS tour connecting cluster centroids is $L_K = K\delta$. The centroid approaches the perimeter as the cluster becomes narrower, so the tour length increases with the number of clusters to reach approximately 66.7% of the perimeter of the sensing field as shown in Figure 5(a). This result differs from [3], which shows that the optimal tour of the mobile BS is the perimeter of the sensing field because of the use of a different data collection scheme. In [3] the network sensor nodes send their data directly to the BS; however, in our work, data is sent to cluster heads which then forward it to the BS.

Now, let us consider the effect of delay requirements on the tour length, L_m. We consider two cases as follows.

Case I: Relaxed Delay Requirement. Assume the delay constraint $L > L_K$. In this case VCHs do not need to shrink in from the centroid, thus $L_m = L_K$. The distance between VCHs is L_m/K, so the transmission ranges of VCHs do not overlap when $L_m/K \geq 2r$. The maximum number of clusters can be obtained when the time the BS spends in each cluster is T_C, that is, when the length of the tour segment within each cluster is equal to $2r$ as shown in Figure 4(b), so, $K_{\max} = L_m/2r$. Moreover, the internal angle of the clusters in this case is $\theta_{K_{\max}} = 2\pi/K_{\max}$.

In order to determine $K_{\max}$, substituting $L_m = L_K$ and $L_K = K_{\max}\delta$, we have $\delta = 2r$ and $\delta = 4RK\sin^2(\pi/K)/3\pi$, with $K = K_{\max}$, gives $4R\sin^2(\pi/K_{\max}) = 6r\pi/K_{\max}$. There is no closed-form solution to this equation, so we use the Taylor series approximation for small values of $\theta_{K_{\max}} = 2\pi/K_{\max}$. Taking into account that the number of clusters is an integer, we find that the maximum number of clusters is $K_{\max} = \lfloor 2\pi R/3r \rfloor$. The maximum number of clusters increases with increasing network radius since the position of the cluster centroid moves towards the perimeter of the sensing field.

Case II: Restrictive Delay Requirement. Assume that the tour length must be less than L_K ($L_m < L_K$). We choose $L_m = L$. The VCH (indicated by "×" in Figure 4(a)) must move in from the centroid, closer to the centre of the sensing field. The maximum number of clusters can be obtained when the length of the tour segment within each cluster is equal to $2r$, so the maximum number of clusters is $K_{\max} = \lfloor L/2r \rfloor$.

In summary, the maximum number of clusters is given by

$$K_{\max} = \begin{cases} \left\lfloor \dfrac{2\pi R}{3r} \right\rfloor & L \geq \dfrac{4\pi R}{3} \text{ (Relaxed)}, \\ \left\lfloor \dfrac{L}{2r} \right\rfloor & L < \dfrac{4\pi R}{3} \text{ (Restrictive)}. \end{cases} \tag{5}$$

The smallest valid scenario is $R = 2r$. In any reasonable scenario, this would correspond to the relaxed case, so $K_{\max} = 4$. However, in this case the transmission ranges of cluster heads overlap when $K = 2$ or $K = 3$. In realistic scenarios, $R \gg 2r$, thus $K_{\max} > 4$. As R increases, $K_{\max}$ increases, up to some point when the restrictive case is triggered. For example, when $R = 5r$, the maximum number of clusters is $K_{\max} = 10$ if $L \geq L_K$, but if $L = 0.5L_K$ (restrictive case), then $K_{\max} = 5$.

To ensure the tour is no longer than L, each VCH needs to find a corresponding real cluster head. Referring to Figure 4(b), the probability that a single node lies in the region *oabc* is equal to the ratio of the area bounded by *oabc* to the area of sensing field, $A = \pi R^2$, that is, $p = RL\sin(\pi/K)\cos(\pi/K)/3\pi^2R^2$. For n network nodes, the probability of finding a real cluster head is

$$Pr = 1 - (1 - p)^n. \tag{6}$$

Figure 5(b) shows that the probability of finding a real cluster head decreases with the number of clusters and with decreasing tour length. Referring to Figure 5(b), when $K_{\max}$ is equal to 10 and 5 for L equal to L_K and $0.5L_K$, respectively, we see that the corresponding probability of finding a real cluster head is approximately one for both cases.

Since the real cluster head is close to, but not at the VCH, the transmission ranges of real cluster heads may overlap. The probability that real cluster head transmission ranges overlap increases with the number of clusters and decreasing node density.

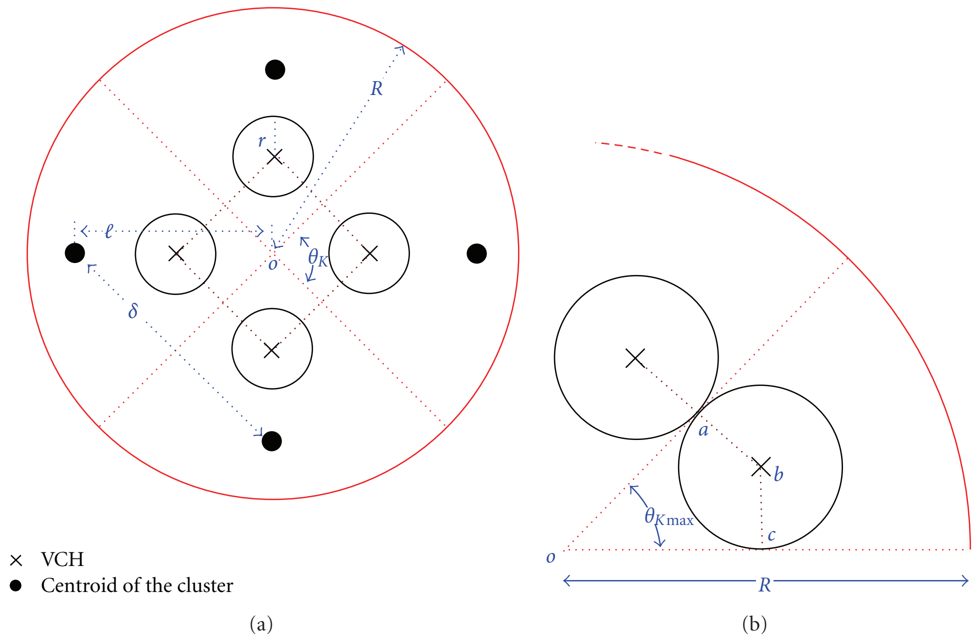


FIGURE 4: The maximum number of clusters. (a) Transmission range of VCHs is not overlapped. (b) Probability of finding real cluster head is proportional to the ratio of the area *oabc* to the sensing field.

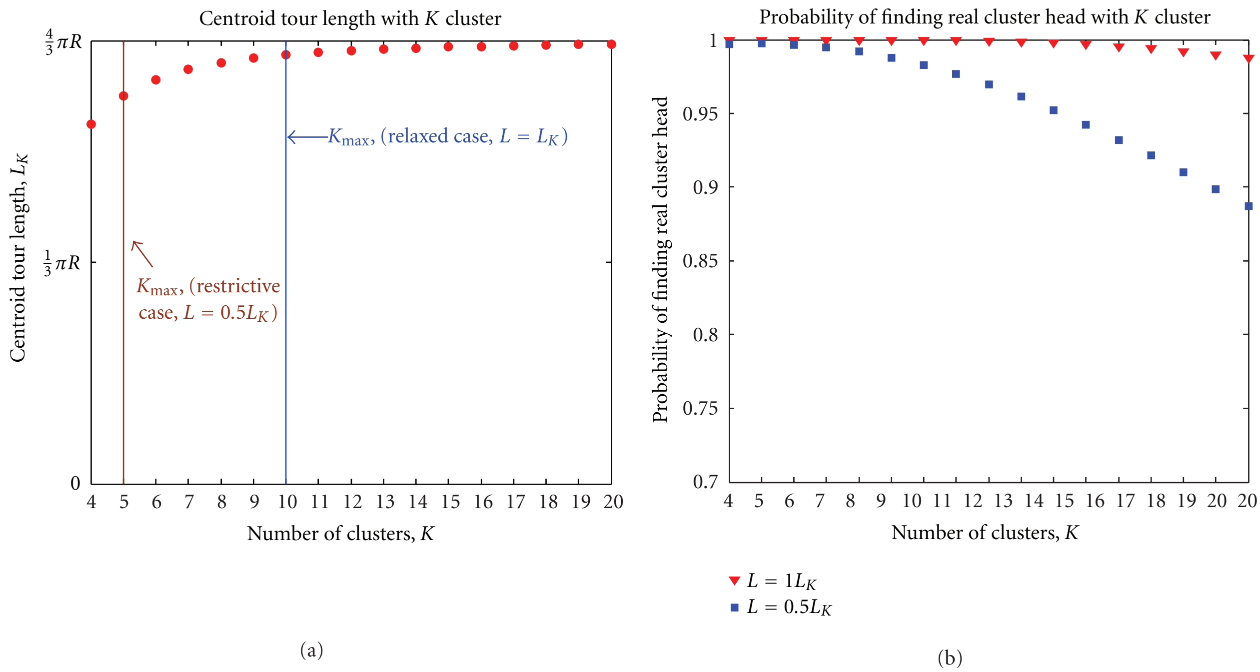


FIGURE 5: The effect of number of clusters on the BS tour and the probability of finding a real cluster head. (a) The BS tour when $r = 1$ and $R = 5r$. K_{max} is calculated from (5) at relaxed delay requirement. (b) The probability of finding a real cluster head, $n = 200$, $r = 250$, and $R = 5r$, from (6).

6. Analysis

In this section, we study the effect of data gathering delay, node density, and network radius on network lifetime. We also determine the upper bound of network radius as the node density, and the velocity of BS varies. Finally, we determine the maximum velocity the BS can move for data gathering such that there is no packet loss for a particular node density. In this section, we assume that the number of clusters equals K_{max} from (5).

6.1. Network Lifetime. Assume E_I is sensor node initial energy, and E_p is the average amount of energy required to transmit one packet. The amount of energy used by a cluster head in one cycle is nE_p/K. Thus, the expected network lifetime is

$$E(\text{Lifetime}) \approx \frac{E_I L_m}{E_p V_m n_K}, \quad (7)$$

where L_m/V_m is the time required for the BS to complete one cycle. Equation (7) represents the maximum network lifetime that can be achieved when n sensor nodes are evenly distributed in K clusters. We can see that increasing the size of the network requires corresponding increase to the number of clusters in order to maintain network lifetime. In the following, we study variation to network lifetime with the network radius, assuming that the number of clusters is at its maximum value.

In this research, we use node degree as a measure of node density (rather than the number of nodes in a unit area), since it reflects the number of nodes that can be accessed using the maximum transmission range. Since the network nodes are uniformly distributed in the network field, then the average node degree is $d = n(\pi r^2/A)$. Substituting for $n_K = n/K$ into (7), then the expected network lifetime is $E(\text{Lifetime}) \approx (E_I L_m K r^2)/(E_p V_m d R^2)$. Let the number of clusters be equal to $K_{\max}$, then using (5) the expected network lifetime is

$$E(\text{Lifetime}) = \begin{cases} \dfrac{8\pi^2 E_I r}{9E_p V_m d} & \text{(Relaxed)}, \\ \dfrac{E_I L^2 r}{2E_p V_m R^2 d} & \text{(Restrictive)}. \end{cases} \quad (8)$$

Equation (8) shows that the network lifetime does not depend on network radius for the relaxed delay requirement. This is because decreases in network lifetime due to increasing node density are canceled by increase in network lifetime due to increasing tour length and number of clusters. However, for the restrictive delay requirement, the network lifetime deceases with decreasing BS tour length and increasing network radius. Therefore, if it is required to achieve a certain level of network lifetime for a large-network scale, then using a single mobile BS may be insufficient, even if we use $K_{\max}$ cluster. It may be necessary to consider multiple mobile BSs as proposed in [15].

6.2. Packet Loss. Network lifetime decreases with increase to network radius, since the number of nodes in each cluster increases for a constant transmission range and node density. However, the time the cluster head contacts the BS depends on the transmission range of the cluster head and BS speed. Thus, there is no packet loss if $T_R \geq T_{pks}$, so the upper bound of the network radius is given by

$$R \leq \begin{cases} \dfrac{2\pi r\left(2r - T_{rq} V_m\right)}{3V_m T_P d} & \text{(Relaxed)}, \\ \sqrt{\dfrac{Lr\left(2r - T_{rq} V_m\right)}{2V_m T_P d}} & \text{(Restrictive)}, \end{cases} \quad (9)$$

where we have used $T_R = 2r/V_m - T_{rq}$ and $T_{pks} = n_K T_P$ and (5) and assume the nodes are equally distributed among the clusters. Equation (9) shows that the upper bound of network radius decreases with the increasing of BS velocity and node density in relaxed delay requirement, while the upper bound of network radius depends on the length of the required BS tour in addition to BS velocity and node density in restrictive delay requirement. For example, for network parameters, $r = 100$ m, $V_m = 2$ m/s, $T_{rq} = 10$ ms, $T_P = 200$ ms, and $d = 15$. For the relaxed and restrictive ($D = 20$ minute) delay requirements, the approximate upper bound of network radius such that there is no packet loss is $R \leq 6.98$ km and $R \leq 2$ km, respectively, where km is kilometer.

More accurately, we can find the probability function and the CDF of number of packet losses at different network radii using (4), at relaxed delay requirement, the approximate value of $K_{\max}$ appearing in (5) when $L = L_K$. The CDF of the number of packet losses is shown in Figure 6(a), using the same network parameters mentioned. The results show that the probability of high packet loss per cluster increases with network radius. Moreover, the number of clusters needed also increases; therefore, the total packet loss increases with network radius. However, controlling the speed of the BS can help to decrease the number of packet losses. The BS could decrease its speed when it moves within a cluster with a large number of sensors, so that it gets enough time to collect packets of all cluster sensors, and increase its speed in clusters with lower numbers of sensor nodes.

Even controlling the speed of the mobile BS can help to reduce the number of packet losses due to unequal numbers of nodes in the clusters; there are definitely a number of packet losses if $R > 6.98$ km. In order to achieve no packet losses as the network scale increases, multiple mobile BS could be used to cooperate for data gathering. The network field could be divided into subnetworks with each mobile BS collecting data from one subnetwork.

6.3. Maximum Velocity of the Mobile BS. When the speed of the mobile BS increases, the minimum number of clusters needs to be increased in order to reduce the number of nodes in the cluster so that the BS can collect cluster data within T_R time, as shown in Figure 6(b). Thus, the maximum speed of mobile BS is determined when the minimum number of clusters increases to reach the maximum number of clusters, $K_{\min} = K_{\max}$. Using (2) and (5), the maximum speed of mobile BS is

$$V_{\max} = \begin{cases} \dfrac{4\pi r^2}{2\pi r T_{rq} + 3RdT_P} & \text{(Relaxed)}, \\ \dfrac{2Lr^2}{LrT_{rq} + 2R^2 d T_P} & \text{(Restrictive)}. \end{cases} \quad (10)$$

Equation (10) shows that the maximum speed of the BS decreases with increase to network radius and decreases even faster in the restrictive delay requirement case, for example, for network parameters, $r = 100$ m, $R = 1$ km, $T_{rq} = 10$ ms, $T_P = 200$ ms, and $d = 15$, the maximum speed of the mobile BS, $V_{\max} = 13.9$ m/s and $V_{\max} = 10$ m/s, at relaxed and restrictive ($L = 3$ km) delay requirements, respectively.

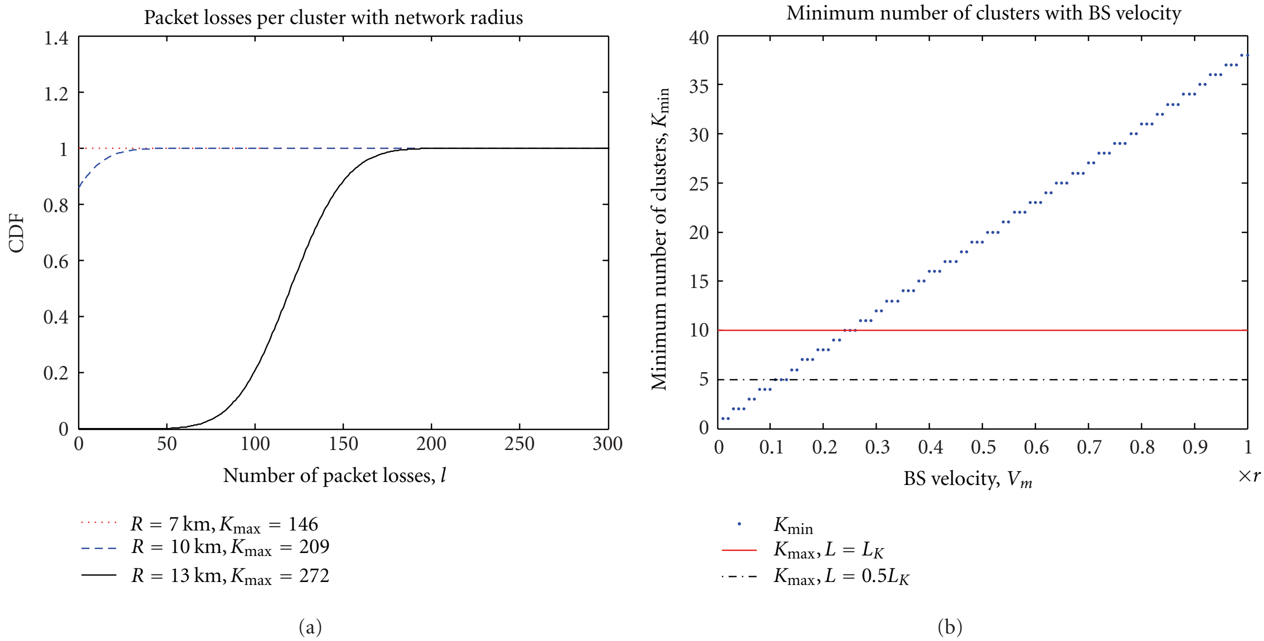


FIGURE 6: (a) The CDF of packet losses, (4) at relaxed delay requirement. The approximate upper bound of network radius $R \leq 4.64r$ from (9). (b) The approximate K_{min} and K_{max}, from (2) and (5), respectively, with BS velocity when $R = 5r$.

7. Practical Implications of Analysis

Here we consider the use of a mobile BS in practical data gathering applications. The transmission range of sensor nodes varies significantly for different applications. In addition, different types of mobile entities can be used for carrying the BS, for instance, a mobile robot, car, train, or UAV plane, so there is a large range for the velocity of the mobile BS.

Assume that a mobile robot that moves at average velocity 2 m/s carries the BS and sensor transmission range equals 100 m. When the sensor nodes are clustered with the maximum number of clusters, then there is no packet loss if the network radius is less than 6.98 km for relaxed delay requirements (refer to (9) with $T_{rq} = 10$ ms, $T_P = 200$ ms, and $d = 15$). In this case, the BS tour takes approximately four hours for gathering sensing data since the tour length is approximately 30 km, which may be applicable for some applications, but much too slow for others.

Assume that sensing data needs to be collected within 20 minutes. Then the maximum network radius must be decreased to be less than or equal to 2 km in order to achieve no packet loss. However, the network radius can be expanded further if sensor nodes with higher transmission ranges are used. For example, if the sensors transmission range increases to be 250 m, then network radius can be less than or equal to 5 km.

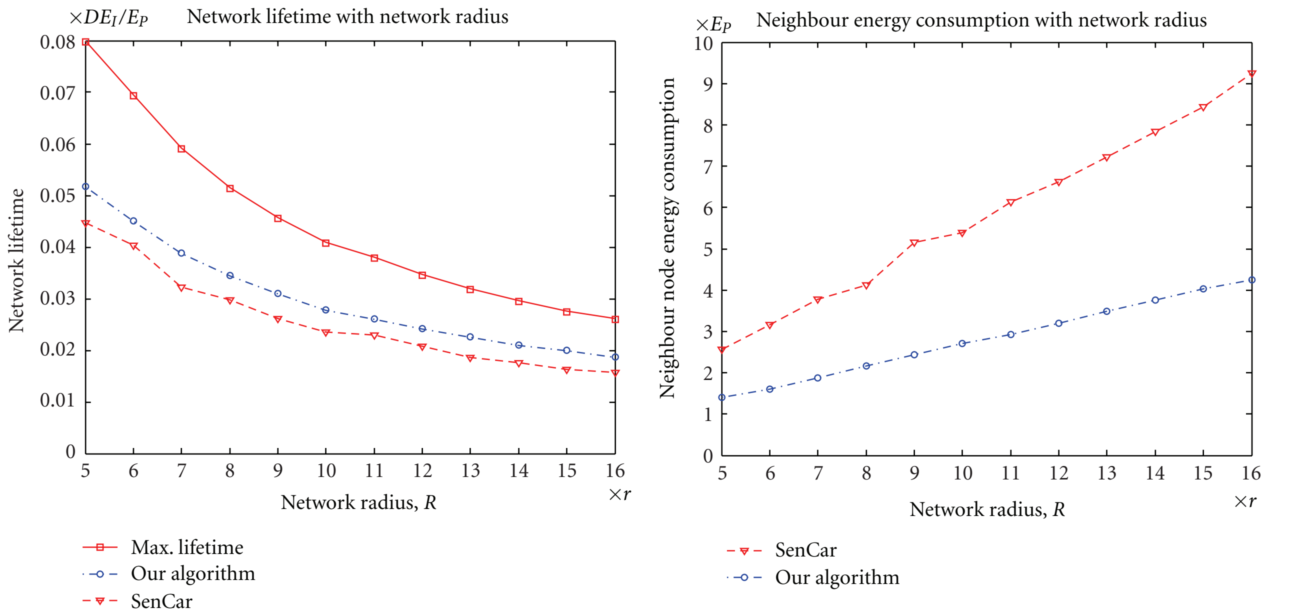
It is also possible to expand the network while reducing data gathering delay for relaxed delay requirements by increasing the speed of mobile BS using, for example, a UAV plane. In this case, the average speed of BS is 100 km/h (the velocity of some military UAV planes is higher than 200 km/h), and sensor transmission range equals 100 m. Then there is no packet loss if the network radius is less than or equal to 5 km. In this case, sensing data can be gathered within approximately 13 minutes.

In our algorithm, it is assumed that the mobile entity can freely move in the sensing field. However, in some situations this is not applicable, for example, when there are obstacles in the moving path of the robot. This may increase data gathering delay since the BS has to find an alternative path to avoid the obstacles.

In addition, the distribution of sensor nodes in the sensing field has a significant effect on the network connectivity. The probability of network partitioning increases when the sensor nodes are nonuniformly distributed or the node degree is less than eight [24, 25]. In this case, the BS has to visit all the sub-networks for data gathering; thus, the location of the sub-networks has to be considered in the calculation of maximum tour length.

As the network becomes more sparse, eventually no clustering is possible. In the limit, all nodes are disconnected, and the BS has to visit the transmission range of all sensor nodes and collect data using single-hop communication. In such a situation, the shortest BS trajectory can be found using the travel salesman problem (TSP) algorithm. The network lifetime is significantly longer than if clustering is employed however, the BS takes a long time for data gathering since it has to visit all sensor nodes.

It has been assumed that the signal attenuation in communication between sensor nodes and the BS is due only to path loss related to distance transmitted. However, the wireless channel such as path loss and interference affects the reliability of communication specially between



(a) (b)

Figure 7: (a) Network lifetime as it varies with network radius, for our algorithm, SenCar algorithm, and the maximum lifetime. (b) The energy consumption for neighbouring sensor nodes of a cluster head for our algorithm and SenCar algorithm as the network radius is varied.

the cluster heads and the BS. The selection of cluster heads can include cross-layer considerations by modifying the metric for selection of real cluster heads. In addition to considering the distance to the virtual cluster head, the reliability of communication can be included.

8. Performance Evaluation

In this section, we evaluate the performance of the proposed algorithm through simulations with MATLAB, assuming that the effect of the MAC layer is ignored.

We assume that sensor nodes in the network are randomly deployed with uniform distribution in a circular sensing field with radius of $R = 1250$ m. Each sensor node has a transmission range of $r = 250$ m ($R = 5r$) and the initial energy of E_I unit. All data packets have a fixed length and take E_P units of energy per packet. The speed of the mobile BS is assumed to be $V_m = 0.18r$ m/s. The packet propagation time is $T_P = 200$ ms, and data request time is $T_{rq} = 100$ ms. We vary the number of nodes in the network to emulate the change in the node degree. We use the node degree as a metric of node density. For each instance of deployment, the network performance metrics are calculated, and the result is the average over 100 instances for each node degree.

8.1. Varying Network Scale. We first study the effect of changing the radius of the network field on the network performance. To evaluate the network lifetime of the proposed algorithms, we calculate the maximum network lifetime from (7), which assumes all clusters have the same number of nodes. The maximum network lifetime is used as a performance benchmark to see how far away the proposed solutions are from the optimal. We compare our algorithm with the SenCar algorithm proposed in [17]. The moving trajectory of the SenCar (mobile BS) consists of a series of connected line segments, and sensors are organized into clusters. The sensor nodes that are nearest to the line segment (which we will refer to as cluster heads) consume more energy than other nodes since they have to forward sensing data to the BS.

The SenCar algorithm assumes a rectangular sensing field and does not implement a closed trajectory for the BS. In order to compare with our algorithm, we assume the SenCar BS moves out across the top half of the circular sensing field and returns across the bottom half.

In our algorithm the number of nodes in the clusters may not be equal since clustering is based on equal subareas. Thus, the cluster head that has to forward the highest number of packets to the BS represents the network bottleneck and determines the network lifetime. Figure 7(a) shows the network lifetime delivered by using our algorithm compared with the SenCar algorithm and the maximum lifetime for the same numbers of clusters. It can be seen that under different network radii, the network lifetime for our algorithm is higher than that for the SenCar algorithm. This is because our algorithm balances the network load among the cluster heads by dividing the sensing field into equal areas. In contrast, clusters in the SenCar algorithm have fixed width but varying area; therefore, the cluster heads that are close to the centre of the sensing field consume more energy than the others. The results also show that the network lifetime decreases as the network radius increases. This makes sense

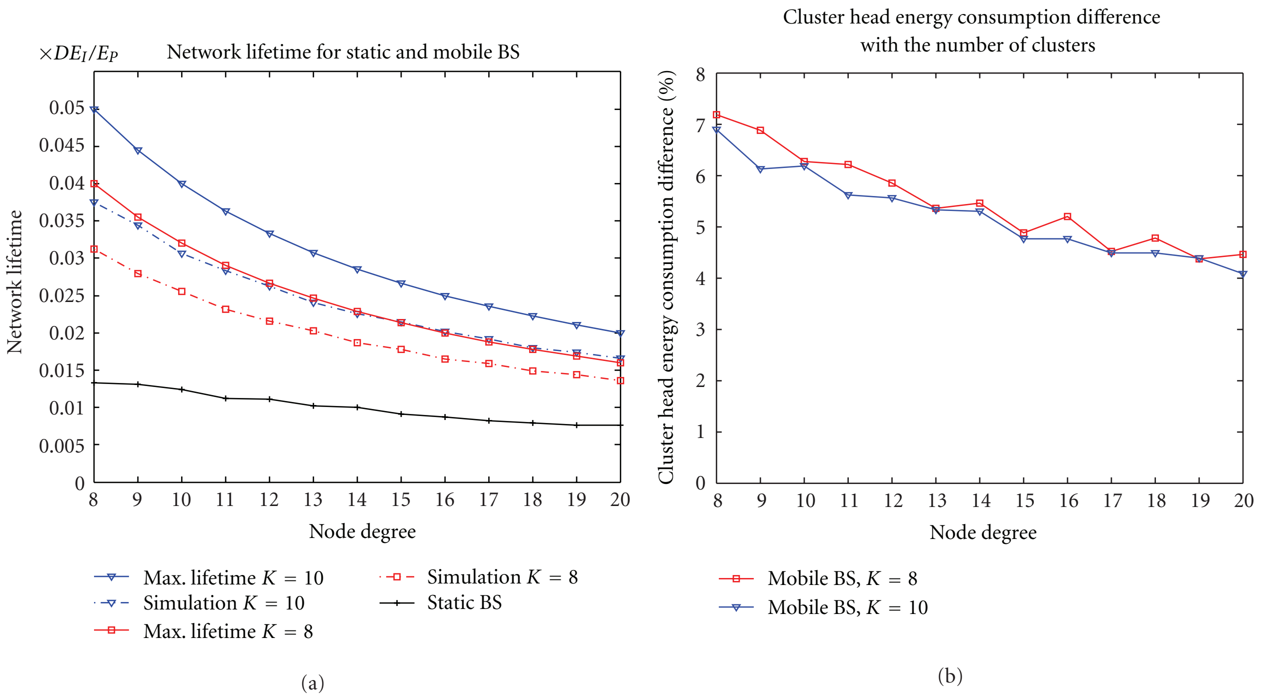


FIGURE 8: (a) Network lifetime as it varies with node degree, for static and mobile BSs with different K. The maximum network lifetime is calculated from (7), which assumes all clusters have the same number of nodes. (b) The minimum and maximum energy consumption differences among the cluster heads as the node degree is varied.

because the number of packets that need to be forwarded to the BS increases.

To study the effect of the position of cluster heads on the cluster sensor node load balance, the maximum energy consumption for a sensor node neighbouring a cluster head is calculated as shown in Figure 7(b) for our algorithm and the SenCar algorithm. The BFS algorithm is used to find the routing tree for each cluster, where the cluster head is the root of the tree.

The results show that the neighbour nodes in our algorithm consume lower energy than the neighbour nodes in the SenCar algorithm. This is because in our algorithm the cluster head and its neighbours are located very close to the centre of the cluster area. On the other hand, the location of neighbour nodes in the SenCar algorithm depends on the line segments of the BS trajectory. When the location of the cluster head is close to the border of the sensing field, some of its neighbours are responsible for forwarding a larger number of cluster-node packets to the cluster head and hence consume more energy than the others. The results also show that energy consumption increases with the increase in the network radius due to increasing the number of cluster sensor nodes.

8.2. Varying Number of Clusters. We then vary the number of clusters and investigate the change in the network lifetime. Figure 8(a) shows the network lifetime delivered by using the mobile BS compared with the static BS, assuming that the static BS is located at the centroid of the sensing field. The breadth first Search (BFS) algorithm is used again to find a routing tree rooted at the BS. In the case of a static BS, the BS neighbouring sensor nodes consume more energy than any other sensor nodes in the network since they have to relay the packets received from child sensor nodes to the BS, while in the mobile BS, the cluster heads consume more energy than the other sensor nodes in the network. The network lifetime using the static BS is compared with the maximum and simulated network lifetime of the mobile BS with different numbers of clusters.

Figure 8(a) shows that the network lifetime decreases as the node degree increases. This makes sense since that increases the number of packets that need to be forwarded to the BS. It can also be seen that as the node degree increases, the difference between the maximum and simulation network lifetime decreases. The reason for this decrease is that the distribution of nodes in each cluster area becomes more even, so the number of packets the cluster heads need to forward become, more balanced.

To evaluate the variation in energy consumption among the cluster heads, we calculate the ratio of difference in cluster head energy consumption to the total energy consumption. The result, shown in Figure 8(b), shows that the percentage of energy consumption difference decreases with the increasing of node degree. The result also shows that the percentage of cluster head energy consumption difference decreases with the increasing of the number of clusters since that decreases the number of nodes in each cluster.

To study the effect of the number of clusters on the cluster sensor nodes load balance, the energy consumption for neighbouring sensor nodes of a cluster head is calculated

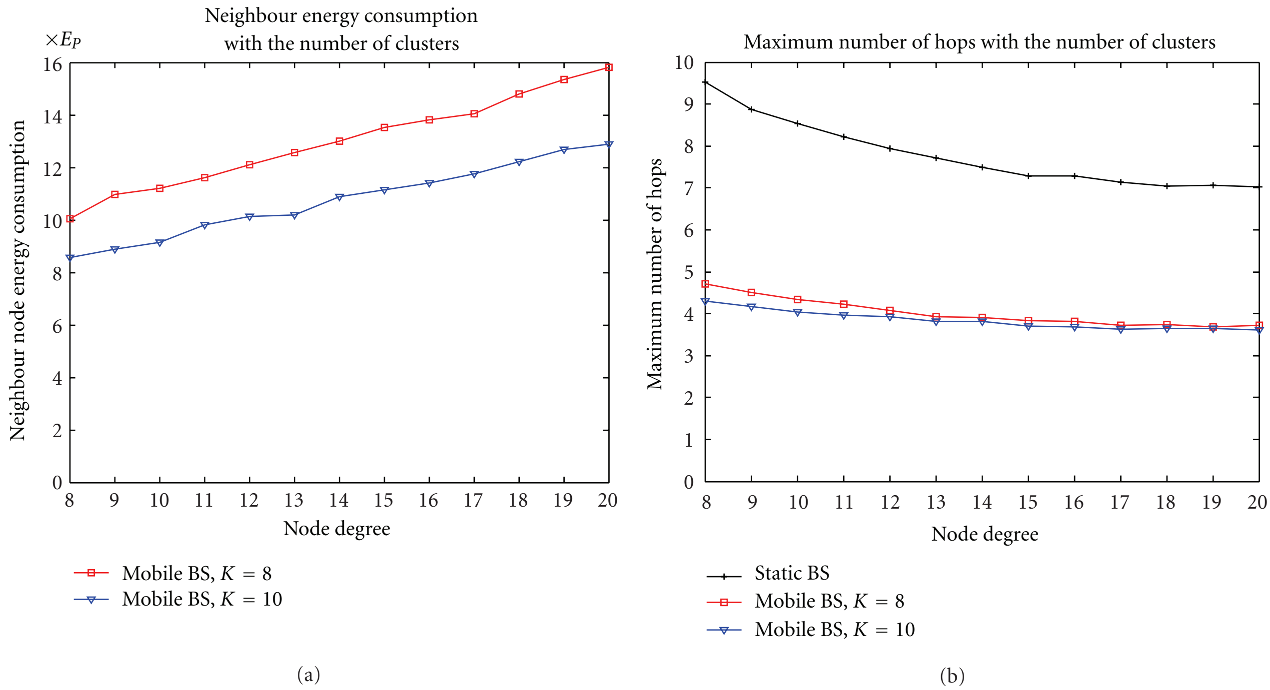


FIGURE 9: (a) The energy consumption for neighbouring sensor nodes of a cluster head as the node degree is varied, for various numbers of clusters. (b) The maximum number of hops as it varies with the node degree, for static and mobile BSs.

as shown in Figure 9(a). The BFS algorithm is used again to find the routing tree for each cluster, where the cluster head is the root of the tree. The curves in Figure 9(a) show that the energy consumption increases, with the decrease in the number of clusters due to increasing the number of cluster sensor nodes, and that the neighbouring sensor nodes are responsible for forwarding their data packets to the cluster head. It is also shown that the energy consumption increases, with the increase in the number of network nodes.

Figure 9(b) illustrates the number of relay hops for the sensing data to reach the BS. To find the maximum number of hops, we have to consider the number of hops of sensor nodes located near the border of the cluster area for the mobile BS case, while the sensor nodes near to the border of the entire sensing field are considered for the static BS case. The maximum number of hops increases with the decrease in the number of clusters for the mobile BS, since that increases the distance between a sensor node and its cluster head. The result shows that the maximum number of hops is still less than that for the static BS. Nevertheless, it also shows that the node degree has a small effect on the maximum route length, due to the fact that the maximum number of hops is proportional to the length of the shortest path, since the density of the sensor nodes in the network is high.

The effect of number of clusters on percentage of the network packet loss is shown in Figure 10. The number of packet losses increases with the node degree and decreasing number of clusters, since that increases the number of packets the cluster heads have to forward to the BS within the contact time. Using (2), the approximate minimum

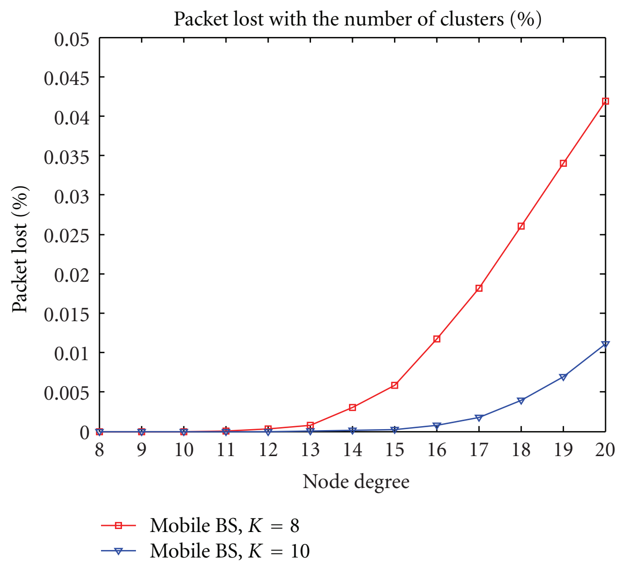


FIGURE 10: The percentage of network packet loss as the number of network sensor nodes is varied, for various numbers of clusters.

number of clusters is as shown in Table 2. The approximate maximum number of clusters is 10, from (5) at relaxed delay requirement. Comparing the number of clusters with the approximate minimum number of clusters, we notice that there is packet loss even when the number of clusters equal or are greater than the minimum number of clusters. This

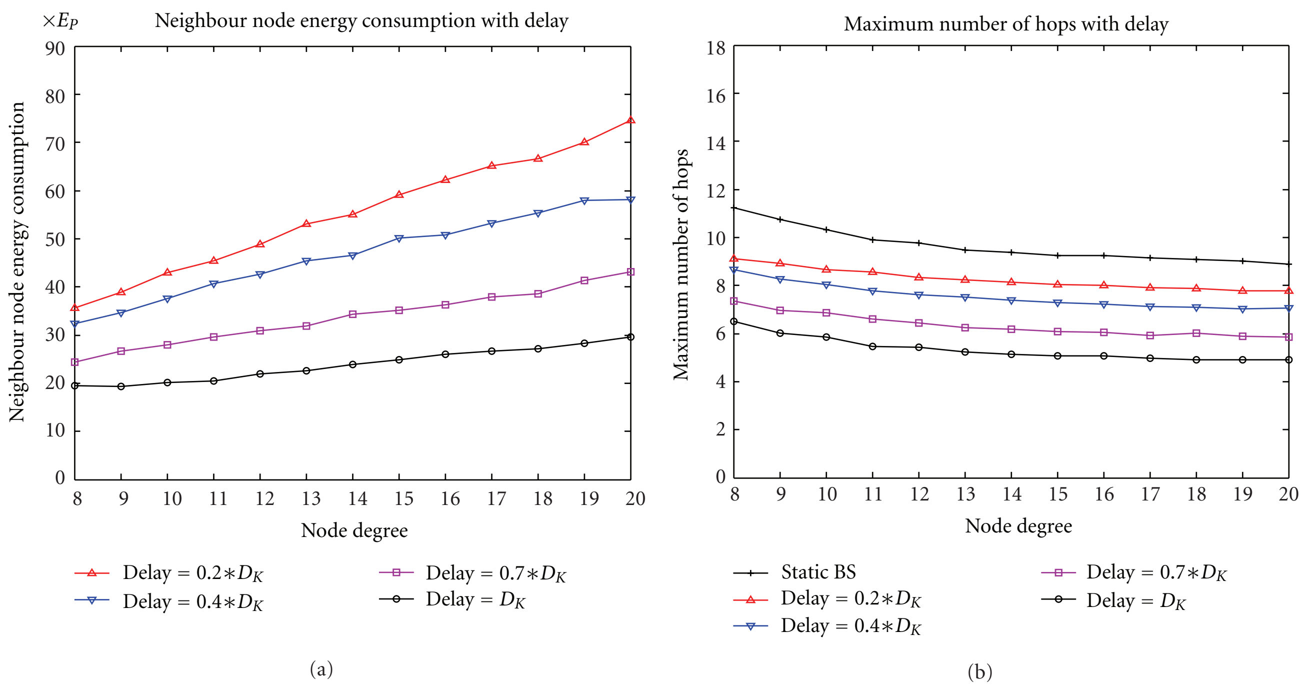


FIGURE 11: (a) The minimum cluster head neighbouring sensor nodes energy consumption as the node degree is varied, for various data gathering delay. (b) The maximum number of hops as it varies with the node degree, for static and mobile BSs.

TABLE 2: The approximate minimum number of clusters as it varies with node degree, from (2). The approximate $K_{\max} = 10$, from (5) at relaxed delay requirement.

Node degree	8	9	10	11	12	13	14	15	16	17	18	19	20
$K_{\min}$	4	5	5	5	6	6	7	7	8	8	9	9	10

is because the sensor nodes are not equally clustered so that some cluster heads have to forward more data packets to the BS than others.

8.3. Varying Data Gathering Delay. We finally study the effect of the data gathering delay on the load balance of cluster sensor nodes when the number of clusters is $K = 6$. We define D_K as the time required for the mobile BS to take a tour connecting centroid points of the clusters. The energy consumption for neighbouring sensor nodes of a cluster head is shown in Figure 11(a). The BFS algorithm is used again to find the routing tree for each cluster. The results show that the energy consumption increases, with the decrease in the end-to-end data gathering delay due to the decreasing length of the BS tour towards the centroid of the sensing field. Therefore, it leads to an increase in the number of sensor nodes, that the neighbouring sensor nodes are responsible for forwarding their data packets to the cluster head. The effect of data gathering delay on the maximum number of relay hops is shown in Figure 11(b). The maximum number of hops increases with the decrease in data gathering delay for the mobile BS, since that increases the distance between a sensor node and its cluster head. The results show that the maximum number of hops is less than that for the static BS. The results also show that the node degree has a small effect on the maximum route length, since the density of the sensor nodes in the network is high.

9. Conclusion

In this paper, we dealt with the problem of data gathering in the mobile BS environment subject to the sensing data needed to be gathered at a specified delay. We proposed a clustering-based heuristic algorithm for finding a trajectory of the mobile BS to balance the energy consumption among sensor nodes. The algorithm allows the BS to visit all cluster heads within a specified delay. We demonstrated by simulation experiments that the use of clustering with a mobile BS can increase the network lifetime significantly. Furthermore, the proposed solution for finding cluster heads results in a uniform balance of energy depletion among cluster heads. We show how to choose the number of clusters to ensure there is no packet loss as the BS moves between clusters for data gathering. We provide an analytical solution to the problem in terms of the speed of the mobile BS. We also provide analytical estimates of the unavoidable packet loss as the network size increases. We finally conduct experiments by simulation to evaluate the performance of the proposed algorithm. The experimental results show that the use of clustering in conjunction with a mobile BS for data gathering can significantly prolong network lifetime and balance energy consumption of sensor nodes. The results also show that the proposed algorithm outperforms the SenCar algorithm [17] in terms of network lifetime and energy consumption of neighbour nodes of the cluster heads.

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