Designing Energy-Efficient Wireless Sensor Networks with Mobile Sinks

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ABSTRACT

Mobile enable Wireless Sensor Network (mWSN) has been proposed to realize large-scale information gathering via networking wireless sensors and mobile sinks. Some fundamental design parameters in mWSN have been investigated in this article, such as cluster size, sink velocity, transmission range, and packet length. Our contributions include: 1) We propose to use multihop forwarding to form a cluster around the expected position of a mobile sink, in order to guarantee packet delay and minimize energy consumption. 2) Sink velocity should be carefully chosen, in order to make a compromise between sink-sensor meeting delay and message delivery delay. 3) Large transmission range and short packet length are both of benefit to lower the outage probability of packet transmission. Extensive simulations have been designed to evaluate the performance of mWSN in terms of packet delay, energy consumption and outage probability.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Network Communications, Wireless Communications, Distributed Networks*

General Terms

Design, Performance

Keywords

wireless sensor network, mobility, clustering, hierarchy, performance, delay, outage probability

1. INTRODUCTION

Recent years have witnessed rising efforts in exploring applications of wireless sensor networks (WSN) in diverse disciplines [1]. According to the traditional definition of WSNs, a dense and static sensor node deployment is implicitly required. Subsequently, there arise a fundamental problem in WSNs with static topology: the non-uniformity of energy consumption among the sensor nodes. In fact, the nearer a sensor node lies with relative to the sink node, the faster its energy will be depleted. In case of sensor node failure or malfunctioning around sink node, the network connectivity and coverage may not be guaranteed.

Intuitively, there are two solutions to the above two problems. On the one hand, if some sensor nodes withdraw from the network due to energy exhausting such that the network loses necessary connectivity and sensing coverage, there must be other supplementary sensor nodes deployed. On the other hand, the sensor nodes should be capable of finding and reaching the sink node in possibly different positions, whether there be multiple sink nodes or the sink node be able to change its location. The first approach is frequently relating to the design of mobile robotics, therefore we will focus our efforts on the second one: to utilize multiple or mobile sinks.

To realize the goal of large scale wireless sensor network deployment, we have introduced the architecture of mobile enabled wireless sensor network (mWSN), which has taken the heterogeneity and mobility of sensors and sinks into account. mWSN is not unique in adopting mobile relays and three-tier network architecture. Related work include Data MULEs ([2],[3]) and CarTel ([4]). However, the influence of the velocity of mobile relays on network performance has not been fully investigated.

The paper is organized as follows. In Section 2, the architecture of mWSN is reviewed with some application scenarios. Section 3 reveals the most energy-efficient multihop clustering scheme by comparing its performance with that of least-hop count clustering. The influence of mobility on the performance of mWSN with single-hop clustering is analyzed in Section 4. Section 5 concludes the paper.

2. ARCHITECTURE AND APPLICATIONS

It has been recognized that a multi-tiered network structure will enhance the network scalability for large scale deployment, as well as be of benefit to routing and energy efficiency. As illustrated in Fig.1, a mobile and multiradio enabled hierarchical architecture has been designed for mWSN, which consists of three tiers:

- *Sensor Tier*, denoting various types of static sensor devices that are capable of collecting information and resource constrained.

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- *Mobile sink Tier*, is composed of mobile phones, laptops, and other mobile/nomadic devices. The mobile sinks will act as relays for information gathering.
- *Base station Tier*, referring to the final information fusion point, from which the task manager can retrieve data in interest.

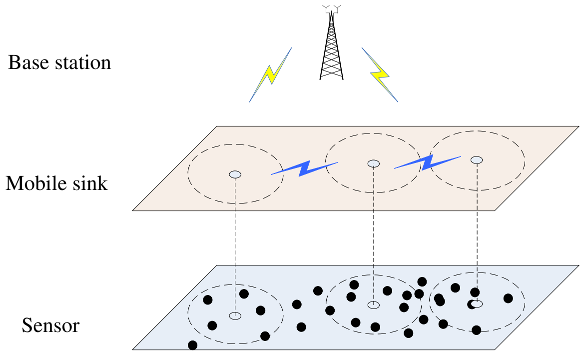
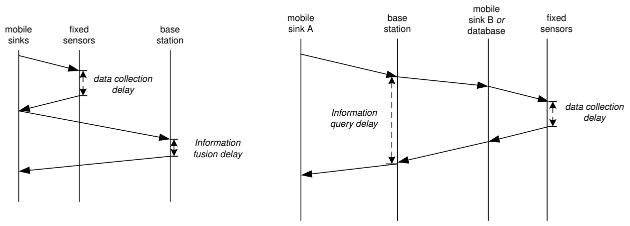


Figure 1: Three-tiered mobile enabled wireless sensor network with cluster structure.

There are mainly two operational modes for mWSN: local sensing and remote sensing. As illustrated in Fig.2(a), when performing *local sensing*, after a mobile sink sending the query command to the fixed sensors and receiving the response, the gathered sensing information will be uploaded to the base station for interpretation. After necessary computation, the query result will be returned to the mobile sink. At the same time, a copy of the query result may be kept in the database for possible subsequent redundant queries. When a mobile phone is requiring *remote sensing* into the network, as illustrated in Fig.2(b), the desired data has to be gathered by other helping mobile sinks firstly. Actually, considering the spatial and temporal correlation characteristics in WSN, we argue that in many cases, the base station will have a copy of the query result which is most similar to the original query. In such cases, there is no need to perform data collection for the second time. Instead, the required information can be read from the database directly.



(a) local sensing (b) remote sensing

Figure 2: Flow charts for two kinds of information query and collection in mWSN.

Remote sensing function is especially useful for mobile phones without certain kinds of sensors. For instances, when a mobile subscriber demands the local weather forecast, and unfortunately his phone has not been equipped with sensors such as temperature, humidity and light sensors, he can turn to the cellular network for recent weather information in the desired region. Let's cite the intelligent transportation system (ITS) as another example, where the traffic light at road crossings and other traffic information in the vicinity can be read from roadside sensors by the mobile sink mounted on the moving vehicle. In most cases, drivers are more interested with the traffic information within nearby blocks and scheduled roads than that in other parts of the city. In order to know whether there is traffic jam in the scheduled route, the driver can send out a retrieval message via cellular networks. If the scheduled route will be too congested for some reason, the driver may change the route accordingly.

3. ENERGY EFFICIENT CLUSTERING IN MWSN

Multi-hop transmission is often favored in wireless sensor networks, not only for reducing channel contention region by long hop transmission, but for the potential energy conservation via multiple short hops from the sensor nodes to the sink node. It seems the more hop count between sending node and receiving node, the lower energy consumption. However, we find this rule does not always hold. Before comparing the energy consumption in single-hop and multihop transmission, we give the energy dissipation model as follows.

The link energy consumption rate due to transmissions between node i and node j can be modeled as

$$E_t(i,j) = \alpha \cdot f_{i,j} \tag{1}$$

$$E_r(j,i) = \beta \cdot f_{i,j} \tag{2}$$

where $E_t(i,j)$ denotes the energy consumed at node i when transmitting to node j with bit rate $f_{i,j}$, $E_r(j,i)$ denotes the energy consumed at node j when receiving from node i with bit rate $f_{i,j}$. While $d_{i,j}$ is denoting the bit transmission distance and d_{max} is the transmission range, the parameter α for sending cost is typically defined as:

$$\alpha = \begin{cases} a + b \cdot d_{i,j}^{\gamma} & \text{when } d_{min} \le d_{i,j} \le d_{max} \\ a + b & \text{when } 0 \le d_{i,j} \le d_{min} \end{cases} \tag{3}$$

where $\gamma = 2$ is the decay factor, $a = 50nJ/bit$, and $b = 100pJ/bit/m^2$. The parameter β for receiving cost typically has the same value as a, i.e. $\beta = 50nJ/bit$. Note that the parameter d_{min} is the threshold under which there is no evident signal attenuation [5]. For instance, for Mica2 motes, the authors of [6] have pointed out that $d_{min} = 2.1m$, which is quite exactly 3 wavelengths.

3.1 Multi-hop vs. Single-hop

In a simple one-dimensional linear network illustrated in Fig.3, without loss of generality, we assume d_{max} is a K integral multiple of d_{min}, Kd_{min}. If the distance between the source sensor and sink node is d_{max}, there are basically two (extreme) alternatives before the source sensor node: directly reach the sink node using the maximal transmission power, and reach the sink node hop by hop along a chain of K relaying sensor nodes with a separation of d_{min}.

For direct single-hop transmission from source node 1 to sink node $K+1$, the energy consumption for one bit will be

$$E_t(1,K+1)+E_r(K+1,1) = 2a+b\cdot d_{1,K+1}^2 = 2a+b(Kd_{min})^2 \tag{4}$$

In the case multihop transmission, the total energy consumption for one bit can be expressed as

$$\sum_{i=1}^{K} E_t(i,i+1) + \sum_{j=2}^{K+1} E_r(j,j-1) = 2Ka + bKd_{min}^2 \tag{5}$$

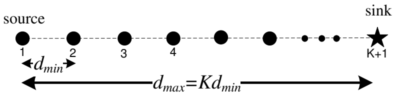


Figure 3: A simple linear network model.

When $\frac{a}{b} \geq \frac{Kd_{min}^2}{2}$, or equally stated, when K is no greater than $\frac{2a}{bd_{min}^2}$, K-hop transmission will not be better than single-hop transmission in perspective of energy conservation. For example, assume $d_{min} = 2m$ and $d_{max} = 150m$, then $K = 75$ and $\frac{2a}{bd_{min}^2} = 250$. Therefore, single-hop outperforms multihop scheme in terms of energy consumption.

A careful investigation of this problem leads to the optimal choice of hop count between source sensor and sink node. From previous study ([7],[8]) we know that, given the distance between the source sensor node and sink node (say D), and the number of hops (say N), the minimum energy dissipation rate for multihop transmission can be achieved when all the hop distances are identical, i.e. $d_{i,i+1} = \frac{D}{N}, \forall i$.

Furthermore, the optimal number of hops, $N_{opt} = \sqrt{\frac{b}{2a}}D$, with $\sqrt{\frac{2a}{b}}$ named *characteristic distance* or d_{char}. Note that such a characteristic distance is independent of D. Only with N_{opt} hops of identical characteristic distance $\sqrt{\frac{2a}{b}}$ can the energy consumption rate be minimized.

In the above example, we find $d_{char} \simeq 30m$, so the optimal hop count is 5, which leads to a lower energy consumption than single-hop transmission with transmission range of d_{max}. In other words, the most energy-efficient scheme is to use single-hop transmission if the separation between sensor and sink is no greater than d_{char}, otherwise multihop with hop distance of d_{char}.

3.2 Characteristic distance based clustering

With mobile phones acting as mobile sinks in mWSN [12], sensors will deliver the gathered information towards mobile phones regarding mobile phones as cluster-heads. As energy efficiency is one of the focal design goals of mWSN system, sensors should choose the most energy-efficient clustering/routing strategy to deliver the collected data. Apparently, the most economic way is to let the sensor node hold sensed data in its buffer until the sink approaches, similar to the proposals in [11] and [2]. However, if the time interval between two successive sensor-sink contacts is rather long (such as in a large scale network), there will be plenty of packets buffered, which could lead to a unacceptable packet delivery delay.

Illuminated by the result explained in previous subsection, we devise an energy efficient clustering scheme based on d_{char}. Assuming that the sink trajectory can be learned or estimated (but not controlled) by each sensor node, and the packet transmission delay is negligible compared to either the accumulative queueing delay in relaying sensor nodes, or the sink approaching delay. Therefore, the packets should be forwarded to the relaying sensor nodes in the anticipated sink vicinity (Fig.4).

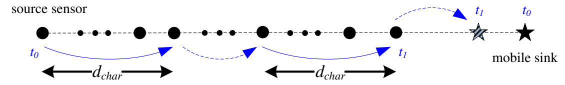


Figure 4: Energy efficient multihop clustering with consideration of message delivery deadline.

To ensure the freshness of sensory information, a deadline as well as the sending timestamp may be carried by every packet. After a packet reception, each sensor shall decide how to handle it by comparing the required deadline T_d with estimated propagation delay T_e. T_e is calculated as the sum of expected sink arrival delay T_{e1} and previously elapsed time before receiving the packet T_{e2}. If $T_d < T_e$, then the packet should be propagated towards the mobile sink as quickly as possible. Otherwise, the packet can be buffered until the sink arrives within a separation of d_{char}. In such a way, packets will be gathered at the sensor nodes around the mobile sink, and delivered to the mobile sink before the packet deadline expires.

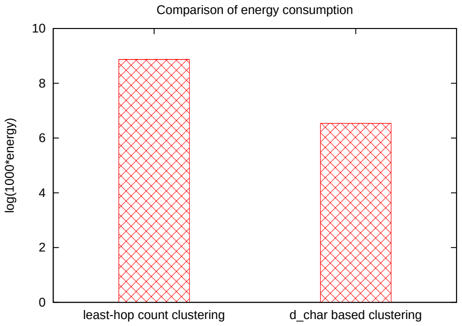


Figure 5: Energy consumption comparison between least-hop count clustering and d_{char} based multihop clustering schemes.

In a simple 1-dimensional scenario with 1000 sensor nodes and one mobile sink, with inter-sensor separation of d_{min} and sink velocity of d_{min} m/s. The mobile sink shall move along the line and collect all the bits from sensors, 1 bit for each sensor. According to the energy model, we evaluate the energy consumption performance of least-hop count clustering scheme (choosing a chain of relay sensors with $d_{max} = 150m$ separation) and d_{char}-based multihop clustering with a packet deadline of $2s$ (choosing relay sensors with separation of d_{char}, the last of which can reach sink before packet deadline expires). From the result shown in Fig.5, we can find the energy consumption of d_{char}-based multihop clustering is less than that of multihop clustering using d_{max} (We have used Logarithmic Y-axis in Fig.5, while the actual energy consumption is 7.0838 and 0.68947 Joules respectively.).

Besides, the less strict the packet deadline, the less energy will be consumed by d_{char}-based multihop clustering. In the above example, energy consumption with packet deadline of $5s, 10s, 20s, 30s$ will be $0.6888, 0.68245, 0.65703, 0.65297$, respectively. This energy saving can be attributed to the reduction of unnecessary packet forwarding actions, with the confident knowledge of sink arrival before packet deadline expires. Similar energy saving can be achieved via increasing the velocity of mobile sink. Due to the page length limitation, we have not provided the results in the paper.

If the sensor density is not high enough, there may not exist sufficient relaying sensor nodes. In this case, sensor nodes have to wait until sink approaches and collect the data. In next section, we turn to study the single-hop clustering scheme and the performance influence from sink mobility.

4. INFLUENCE FROM SINK MOBILITY

Intuitively, increasing the sink velocity v will improve the system efficiency, since in unit time interval the mobile sink can meet more sensors and gather more information throughout the sensor field. However, we should carefully choose this parameter as explained follows. On the one hand, the higher mobile sink velocity, the higher the probability for static sensors to meet mobile sinks. On the other hand, when mobile sinks are moving too fast across the effective communication region of static sensors, there may not be a sufficient long session interval for the sensor and sink to successfully exchange one potentially long packet. In other words, with the increase of sink velocity, the “outage probability” of packet transmission will arise[1]. Therefore, finding a proper value for sink velocity must be a tradeoff between minimizing the sensor-sink meeting latency and minimizing the outage probability.

4.1 Sensor-sink meeting delay

Suppose the network consists of m mobile sinks and n static sensors in a disk of unit size (of radius $1/\sqrt{\pi}$). Both sink and sensor node operate with transmission range of r. The mobility pattern of the mobile sinks $M_i (i = 1, ..., m)$ is according to “Random Direction Mobility Model” [9], however, with a constant velocity v. The sink's trajectory is a sequence of epochs, and during each epoch the moving speed v of M_i is invariant and the moving direction of M_i over the disk is uniform and independent of its position.

Denote Q_i as the epoch duration of M_i, which is measured as the time interval between M_i's starting and finishing points. Q_i is an exponentially distributed random variable, and the distributions of different $Q_i (i = 1, ..., m)$ are independent and identically-distributed (iid) random variables with common average of $\overline{Q}$. Consequently the epoch length of different L_is are also iid random variables, sharing the same average of $\overline{L} = \overline{Q} \cdot v$.

Assume a stationary distribution of mobile sinks, then the probabilities of independent mobile sinks approaching a certain static sensor from different directions are equal. Specifically, the meeting of one static sensor $N_j (j = 1, ..., n)$ and one mobile sink M_i is defined as M_i covers N_j during an epoch. Since M_i will cover an area of size $\pi r^2 + 2r \cdot L_{i,k}$ (Fig.6) during the k-th epoch, then the number of epochs X_i needed till the first sensor-sink meeting is *geometrically* distributed with average of $\frac{1}{p} = \frac{1}{\pi r^2 + 2r\overline{L}}$ (Theorem 3.1 of [9]), with the cumulative density function (cdf) as

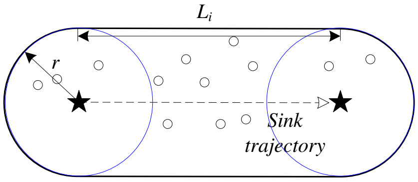


Figure 6: Illustration of computing the distribution of sensor-sink meeting delay.

$$F_{X_i}(x) = \sum_{x_k \le x} p(1-p)^{k-1} \tag{6}$$

In the case of multiple mobile sinks, the sensor-sink meeting delay should be calculated as the delay when the first sensor-sink meeting occurs. Thus the number of epochs X needed should be the minimum of all $X_i (i = 1, ..., m)$, with the cdf as

$$F_X(x) = 1 - [1 - F_{X_i}(x)]^m \simeq \sum_{x_k \le x} mp(1-p)^{k-1} \tag{7}$$

Denote $\overline{X}$ as the average of X, then the expected sensor-sink meeting delay will be

$$D_1 = \overline{X} \cdot \frac{\overline{L}}{v} \tag{8}$$

This result gives us some hints on choosing the parameters to minimize the sensor-sink meeting delay. If we increase the radio transmission range r, or increase the number of mobile sinks m, or increase the sink velocity v, the sensor-sink meeting delay can get reduced.

The above analysis has implicitly neglect the packet transmission delay during each sensor-sink encounters. However, if the message length is not negligible, the message has to be split into several segments and deliver to multiple sinks.

4.2 Large message delivery delay

Message delivery delay can be mainly attributed to the packet transmission time. In case of packet segmentations, the split packets are assumed to be sent to different mobile sinks and reassembled. The packet resequencing delay is out of the scope of our study.

Assume the sensor will alternate between two states, active and sleep, whose durations will be exponential distributed with a mean of $1/\lambda$. Thus the message arrival is a Poisson process with arrival rate λ. For constant message length of L, constant channel bandwidth w, the number of time slots required to transmit a message is $T = \frac{L}{w}$. Then with a service probability $p = m\pi r^2$, the service time of the message is a random variable with Pascal distribution (Lemma

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[1] By *outage* we mean the incident of unsuccessful packet transmission due to the absence of reliable link with duration of a complete packet length between mobile sink and sensor node. Methods such as packet segmentation and buffering can lower such outage probabilities, however, at the cost of increasing packet service time.

1 of [10]). That is, the probability that the message can be transmitted within no more than x time slots, is

$$F_X(x) = \sum_{i=0}^{x-T} \binom{T+i-1}{T-1} p^T (1-p)^i \qquad (9)$$

Such a Pascal distribution[2] with mean value of $\frac{T}{p} = \frac{L}{\pi m w r^2}$. Under an average Poisson arrival rate λ and a Pascal service time with $\mu = \frac{p}{T} = \frac{\pi m w r^2}{L}$, data generation and transmission can be modeled as an M/G/1 queue. Then the average message delivery delay can be expressed as follows:

$$D_2 = \frac{1}{\lambda}[\rho + \frac{\rho^2 + \lambda^2 \rho^2}{2(1-\rho)}] \qquad (10)$$

where $\rho = \frac{\lambda}{\mu}$. For simplicity, we neglect the impact of arrival rate and set λ=1, thus

$$D_2 = \frac{1}{\mu - 1} = \frac{1}{\frac{\pi m w r^2}{L} - 1} \qquad (11)$$

This result shows that, by decreasing message length L, or increasing transmission range r and number of mobile sinks m, the message delivery delay can be reduced.

We have designed simulations to verify our analysis. The data generation of each sensor nodes follows a Poisson process with an average arrival interval of 1s. By varying the ratio of sink velocity against transmission radius, and by varying the number of mobile sinks, we can evaluate the performance of average message delivery delay and energy consumption, as illustrated in Fig.7 and Fig.8.

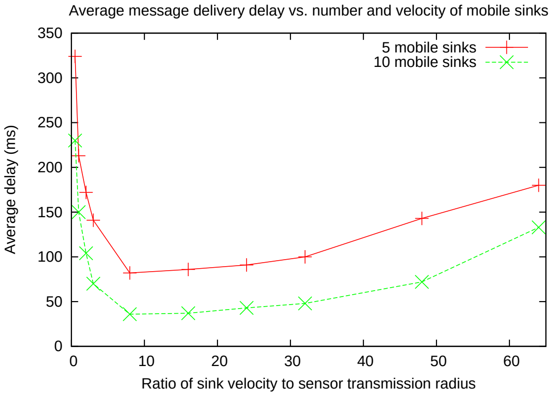

Figure 7: Average message delivery delay under different scenarios by varying the number and velocity of mobile sinks.

As can be found in Fig.7, it coincide with our expectation that the more mobile sinks deployed, the less delay for message delivery between sensors and sinks. Besides, the simulation results are identical with our analysis on choosing the proper speed for mobile sinks. When the sink mobility is low, the sensors have to wait for a long time before encountering the sink and delivering the message. When the sink moves too fast, however, although the sensors meet the sink more frequently, they have to have the long messages sent successfully in several successive transmissions. In fact, there exists an optimal velocity under which the message delivery delay will be minimized.

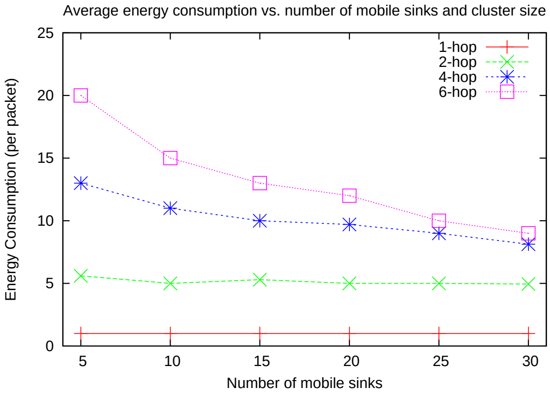

Figure 8: Average energy consumption under different scenarios by varying the number of mobile sinks and cluster size.

Average energy consumption is illustrated in Fig.8. By different cluster size, we mean the maximal hop count between the sensor and mobile sink. It is worthy noting that when the cluster size is small (1 or 2), the average energy consumption will almost remain constant irrespective of the number of mobile sinks. In other words, more deployed mobile sinks will not lead to further reduced energy consumption. However, when messages can be delivered to a mobile sink multiple hops away, then the number of mobile sinks will have influence on the energy consumption: the more mobile sinks, the less energy will be consumed. In fact, the energy consumption in mWSN is more balanced compared with static WSN, which means the remaining energy of each sensor node is almost equal. It is easily understood that more balanced energy consumption will lead to more robust network connectivity and longer network lifetime.

4.3 Outage probability

In the above subsection, we have calculated the service time distribution for one sensor node (with multiple mobile sinks). However, while moving along a predefined trajectory, one mobile sink may potentially communicate with several sensor nodes simultaneously. In order for a successful packet delivery, we are interested in finding the relationship between such parameters as packet length L (number of time slot required is $T = \frac{L}{w}$), transmission range r, sink velocity v, and outage probability p_{outage}.

Let's firstly qualitatively describe the relationship between p_{outage} and r, v, T. To guarantee the packet transmission completed in duration T, we first defined a zero-outage zone, as illustrated by the shaded region H in Fig.9. Nodes lying in H will be guaranteed with zero outage probability, because the link between sensor and sink remains stable for a duration of T with probability 1. Note that H is not identical with the rectangle in [11] where the sensor-sink separation is predefined. The border arc of H is the intersected area of two circles with radius r, and the width of H is determined by $(2r - vT)$. Intuitively, if H is viewed as a queuing system, then the larger the area of H, the higher the service

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[2] Since one sensor is to be served by m sinks, the service probability is the overlapped coverage by m sinks in the unit area, i.e. $1 - (1 - \pi r^2)^m \approx m \pi r^2$.

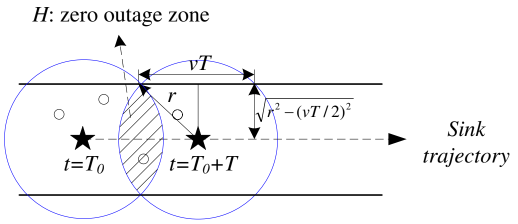

Figure 9: Illustration for computing the relationship between zero-outage probability and r, T.

rate, thus the lower the average outage probability.

The goal of enlarging the area of H can be achieved via increasing r,[3] or decreasing v or T. With constant packet length (i.e. constant T), we can choose to increase r or to decrease v. However, increased r will require for larger transmission power, therefore, it is more energy efficient by decreasing sink velocity v.

Some preliminary simulation results can verify our expectations on the parameter tuning methods. With 3000 sensor nodes and one mobile sink in a 10,000 × 10,000 meters region, when the sink velocity is 15 m/s and transmission range is 80 m, the outage percentage statistics have been shown in Fig.10. We can find that, as analyzed above, the larger transmission range r, or the shorter the packet length T, the lower the outage percentage will be.

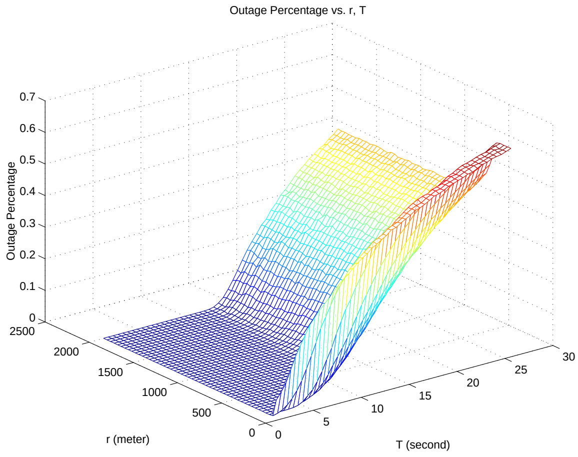

Figure 10: Outage probability vs. r and T.

5. CONCLUSION

Mobile enable Wireless Sensor Network (mWSN) has been proposed to realize large-scale information gathering via wireless networking and mobile sinks. Through theoretical analysis we have found that, by learning the mobility pattern of mobile sinks, d_{char}-based multihop clustering scheme can forward the packets to the estimated sink positions in a timely and most energy-efficient way. Besides, the less strict packet deadline, the more energy saving can be achieved.

In addition, the mobility's influence on the performance of single-hop clustering has been investigated. It is found that sink mobility can reduce the energy consumption level, and further lengthen the network lifetime. However, its side effects are the increased message delivery delay and outage probability. The same problems will remain by tuning the sink density or coverage (i.e. sink amount and transmission range), so we conjecture sink mobility and sink density are permutable, since sink mobility increase its spatial redundancy similar with deploying multiple sinks.

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[3] The area of H is $4 \times (\frac{r^2}{2} \arccos \sqrt{\frac{vT}{2r}} - \frac{vT}{4}\sqrt{r^2 - (\frac{vT}{2})^2})$, which is a monotonous increasing function of $r, r \geq \frac{vT}{2}$.