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mWSN for Large Scale Mobile Sensing

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Abstract. This paper reviews the state-of-the-art features introduced by sink mobility into wireless sensor networks (WSN), and introduces the architecture of mobile enabled Wireless Sensor Network (mWSN) to realize large-scale information gathering via networked wireless sensors and mobile sinks. After introducing the mobile sensing scenarios, some fundamental design parameters in mWSN have been investigated, such as cluster size, sink velocity, transmission range, and packet length. Our contributions include: (1) A cluster formation method has been proposed via 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) Analysis of the performance influence by sink mobility leads to the conclusion that the optimal sink velocity must make a compromise between sink-sensor meeting delay and message delivery delay. (3) Finding that 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 of packet transmission.

Keywords: wireless sensor networks, mobile sink, mobility

1. Introduction

Energy conservation is regarded as one of the most significant challenges in wireless sensor networks (WSN) due to the severe resource limitations of sensor nodes [1]. In addition, the peculiar non-uniform traffic pattern in wireless sensor networks can lead to increased traffic for those sensor nodes close to the sink node. Therefore an unbalanced energy dissipation pattern will be inevitable, and those critical sensor nodes close to the sink node will withdraw from the network earlier due to faster energy depletion. The withdrawal of sensor nodes around sink node has lead to the known "energy hole" problem. The network may consequently lose sufficient connectivity and coverage, if there is no supplementary sensor deployment. Methods such as in-network processing and deploying multiple sinks can only partly tackle this problem by sacrificing the information accuracy and increasing the infrastructure cost.

Different from these approaches for flat networks, we have addressed this problem by leveraging mobility and multi-radio heterogeneity to create a cellular-sensor hybrid system with clustered and tiered network architecture. By combing the rationales in precious approaches such as Data MULE [3] and TTDD [2], the mobile enabled WSN (mWSN [29]) enables both local and remote sensing by mobile phones extracting information of interest from the sensory environment. As illustrated in Fig. 1, there are three tiers in the mWSN architecture: sensor tier, mobile sink tier, and base station tier.

At the sensor tier, sensor nodes as well as various RFID tags may be organized in a clustered fashion with mobile sinks as the cluster heads. At mobile

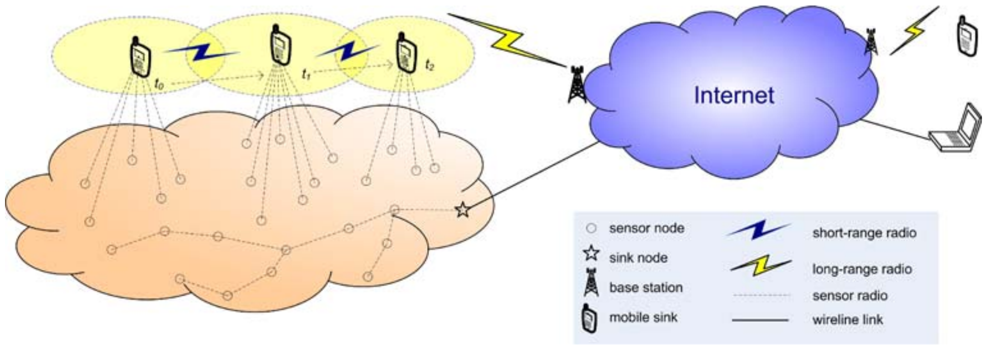

Figure 1. Architecture overview of mobile enabled wireless sensor network (mWSN).

sink tier, mobile sinks may coordinate locally or remotely to exploit the redundancy via short-range or long-range radios equipped with each mobile phone. At the base station tier, gathered sensory information can be stored and forwarded to Internet by the base stations of cellular networks, which serves as the access points to Internet.

mWSN will enhance the performance of network connectivity and coverage by connecting isolated "islands" of wireless sensor networks designed for different applications. As illustrated in Fig. 2, there are basically two sensing modes in mWSN. In the case of local sensing, after mobile sink sends the information query command, sensory information collected by fixed sensors will be firstly forwarded by mobile sink to the base station for information fusion, where the digital information can be parsed and translated into meaningful interpretations. In the case of remote sensing, the mobile sink will send the information query command to the base station, which will assign the sensing task to another mobile sink or fetch the information from a database of sensory information. The differentiation between local sensing and remote sensing may be based on the location information of sensors and mobile sink: if the location of a querying mobile sink is same with those of reporting sensors, it can be decided as a local sensing; otherwise, it should be a remote sensing.

By allowing and leveraging sink mobility and sink coordination, mWSN can achieve the goal of lower and balanced energy consumption with the following features:

- Single-hop clustering. By allowing only single-hop transmission between sensor and sink node, most previous multihop relaying sensor nodes may become unnecessary. In fact, sensor nodes can enter sleep mode until the sink approaches. Therefore, the original energy budget for multihop relaying can be saved.
- Sink mobility and coordination. For a delay-tolerant application, single mobile sink in fact equals virtually multiple static sinks at different

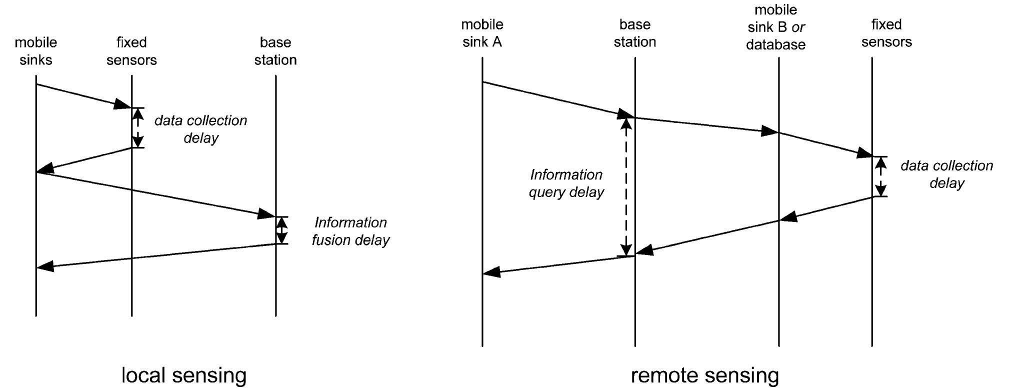

Figure 2. Local sensing and remote sensing in mWSN.

positions. Multi-sink deployment can bring more uniform energy dissipation, therefore the possibility of energy hole will be reduced and network coverage will be improved.

- Mobility-assisted positioning and identification. Sensor nodes can estimate their position by learning mobile sink's position, which can be periodically broadcasted. If each sensor node can be geographically identified, then it is feasible to use more energy-efficient routing method, such as the geographic based routing.

Furthermore, with the knowledge of the remaining energy left at each sensor node, mobile sinks can choose the optimal path by circumventing the least-energy sensor nodes [28]. The direct benefit of energy reduction is the lengthened network lifetime. As the route length can be reduced to one in mWSN, the scalability performance can also benefit from the hierarchical architecture of mWSN. However, the performance of packet delivery delay may be compromised, because packets have to be buffered before mobile sink approaches the sensor nodes. At the same time, the delay performance cannot be improved by simply increasing sink velocity. When mobile sinks are moving too fast through the effective communication region of static sensors, there may not be sufficient long dialogue durations for the sensor nodes to successfully deliver potentially long packets to the mobile sink. In other words, with the increase of sink velocity, the "outage probability" of packet transmission will rise.

To address this issue, we have investigated two methods from the perspectives of sink velocity control and multihop forwarding strategy. In the first approach [29] a mobile sink will determine the optimal sink velocity that makes the best tradeoff between sensor-sink meeting delay and fragmented message delivery delay. This method is based on the knowledge of required message delivery duration and transmission radius of sensor nodes. In the second approach [30], based on the information of sink position and velocity, sensor nodes can estimate the next sensor-sink meeting time. The knowledge of the deterministic sink trajectory is the basis of this estimation. Therefore the sensor nodes can choose an energy efficient multihop forwarding strategy to propagate the packet to the mobile sink before packet deadline expires.

This article is organized as follows. In Section 2, the state-of-the-arts of different approaches are presented regarding how to leverage sink mobility in wireless sensor networks. In the framework of mWSN, Section 3 studies the optimal multihop forwarding strategy if the sink trajectory information is given, Section 4 investigates the optimal sink velocity in single-hop clustering strategy, and analyzes the performance influence of sink mobility on outage probability of packet transmission. Section 5 concludes the article.

2. State-of-the-Arts

The existing approaches exploiting sink mobility can be categorized with respect to the property of sink mobility, communication/routing pattern, and sink amount. According to the obtainable knowledge about sink mobility, there are basically three kinds of sink mobility: random, predictable, and controlled sink mobility. In terms of the hop-count between sensors and sink, there are mainly two communication/routing patterns: single-hop and multihop forwarding. The hop-count between sensors and sink has also defined the cluster radius in clustered wireless sensor networks. Majority of related work studied the mobility of single sink. However, a joint optimization is possible if coordination among multiple sinks is feasible. Table 1 lists the related work by comparing different approaches of leveraging sink mobility. Note here Mobile Base Station (MBS) and Mobile Data Collector (MDC) in [12] are with the same meanings as multihop and single-hop forwarding, respectively.

For random sink mobility [2–10, 18], sensors can only choose to immediately deliver data to approaching mobile sinks, which leads to significant packet dropping due to insufficient sensor-sink communication duration. For predictable sink mobility [16–17, 19–21], sensors can learn the trajectory pattern of mobile sinks in spatial and temporal domains, based on which sensor topology can be adaptively reorganized. For instances, sensors can decide the transmission schedule which can maximize the opportunity of successful data transmission, and we can design routing strategies for more balanced load among sensors. For controlled sink mobility [11–15, 22–27], the optimization problem can be generally classified into two categories: finding the optimal sink trajectory, i.e. the rendezvous based solution or traveling salesman problem that aims to minimize mobile sink visiting time for all the sensor nodes;

Table 1. Comparison of leveraging sink mobility in WSN.

	References	Random, predictable, or controlled sink mobility	Single-hop or multihop forwarding	Single-sink or multiple sinks
Data MULEs, SENMA, DFT-MSN	[3–6]	Random	Single-hop	Multiple
CarTel, Message Ferry	[7–10]	Random	Multihop	Multiple
Mobile Element Scheduling	[11, 12]	Controlled	Single-hop	Single
AIMMS	[13–15]	Controlled	Multihop	Single/multiple
Predictable Mobile Observer	[16]	Predictable	Single-hop	Single
SEAD	[17]	Predictable	Multihop	Multiple
TTDD, EARM	[2, 18]	Random	Multihop	Single
HLETDR, Joint Mobility and Routing	[19, 21]	Predictable	Multihop	Single
Base Station Relocation, Maneuverable Relays	[22–27]	Controlled	Multihop	Multiple

finding the optimal sink location, i.e. to optimally place multiple sinks or relays in order to minimize the energy consumption and maximize network lifetime.

It is well known that the traditional definition for a wireless sensor network is a homogeneous network with flat architecture, where all nodes are with identical battery capacity and hardware complexity, except the sink node as the gateway to communicate with end users across Internet. However, such a flat network architecture inevitably leads to several challenges in terms of MAC/routing design, energy conservation and network management. In fact, as a kind of heterogeneity, mobility can create network hierarchy, and clustering is beneficial to improve network scalability and lifetime. Therefore, the above related works in recent years have coincidently adopted 2-tier or 3-tier architecture, where mobile nodes with high capability form an *overlay* backbone. From simulation studies and theoretical analysis in these works, we can find the following common features and benefits:

- Extended network functional lifetime. This feature is achieved by reducing the relaying overhead and average route length between sensor nodes and sink node. From perspectives of energy-efficiency, single-hop communication should be the optimal one for sensor nodes.
- Improved network scalability. This merit is achieved by lowering overhead of MAC/routing protocols at the vast majority of resource constrained sensor nodes, especially for high-density networks. Complexity of other network maintenance functions such as topology and connectivity control may also get reduced.
- Adaptive network configuration. This feature is achieved through adaptive network re-organization and varying-scale observation based on the observed dynamics of targets being sensed, both in spatial and temporal domains.
- Sacrificed message delay. This defect can mainly be attributed to the increased sensor-sink meeting delay. Methods such as increasing the density of sink nodes and controlling the trajectory of mobile sinks can offset relinquished performance.

In these tiered networks, one shared design rationale is to keep the logics of sensor nodes as simple as possible, and move complex functions to the overlaying mobile elements with richer resources. We also notice that, some more recent work has commenced on applying methods including Delay Tolerant Networking (DTN) and peer-to-peer (P2P) information sharing for asynchronous message switching in challenged wireless sensor networks. Unfortunately, we have not found efficient inter-tier communication methods for such cross-tier optimization approaches.

3. Optimal Multihop Forwarding Strategy Under Predictable Sink Mobility

If the sink mobility is predictable or can be learned in time and space domains [16,19], we may firstly find out the optimal forwarding strategy, however, whether we should choose multihop or single-hop forwarding? In other words, what is the optimal cluster radius if we regard mobile sinks as cluster heads [31]? Prior arts have not studied this specific problem. Before answering this question, we shall firstly reveal the term of "characteristic distance" based on the energy dissipation model in wireless sensor networks.

3.1. Characteristic Distance (d_{char})

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

$$E_t(i,j) = \alpha \cdot f_{i,j}$$
$$E_r(j,i) = \beta \cdot f_{i,j}$$

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:

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

where γ=2 is the decay factor, a=50 nJ/bit, and b=100 pJ/bit/m^2. The parameter β for receiving cost typically has the same value as a, i.e. β=50 nJ/bit. Note that the parameter $d_{\min}$ is the threshold under which there is no evident signal attenuation [32]. For instance, for Mica2 motes, the authors of [33] have pointed out that $d_{\min}$=2.1 m, which is quite exactly three wavelengths.

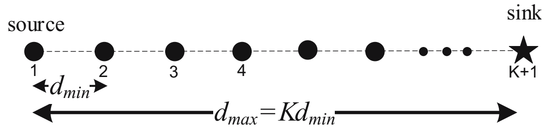

Figure 3. A simple linear network model.

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 (single-hop), and reach the sink node hop by hop along a chain of K relaying sensor nodes with a separation of $d_{\min}$ (multihop). For direct single-hop transmission from source node 1 to sink node K+1, the energy consumption for one bit will be:

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

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

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

Comparing the above results, it is easy to find that, when $\frac{a}{b} \ge \frac{Kd_{\min}^2}{2}$ 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. 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, there is an 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.

Return the above example, we find d_{char}=30 m, 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 it is optimal to use multihop forwarding with per-hop distance of d_{char}.

3.2. d_{char} based Clustering Scheme with Packet Delivery Delay Guarantee

With mobile phones acting as mobile sinks in mWSN, sensors will deliver the gathered information towards mobile phones regarding mobile phones as cluster-heads [31]. 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. 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 an unacceptable packet delivery delay.

Illuminated by the result explained in previous subsection, we devise an energy efficient clustering scheme based on d_{char} with delay guarantee. 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).

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.

Based on the above analysis, we can state the d_{char}-based multihop cluster formation method as follows: in mWSN with mobile sinks as cluster heads, the optimal clustering should consider both energy efficiency and packet delay guarantee. The optimal position of cluster head should be around the expected position of a mobile sink. In order to achieve energy optimality, a chain of forwarding sensor nodes with a separation of d_{char} shall be selected. In order to assure packet delay, the optimal cluster radius shall depend on two factors: required packet delivery deadline and sink velocity. The higher sink velocity and the looser packet delivery delay, the smaller the cluster radius will be.

In a simple 1-dimensional scenario with 1,000 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 an order of magnitude 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 on the packet delivery delay, 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, and 30s will be 0.6888, 0.68245, 0.65703, and 0.65297, respectively. This energy saving can be attributed to the reduction of unnecessary packet

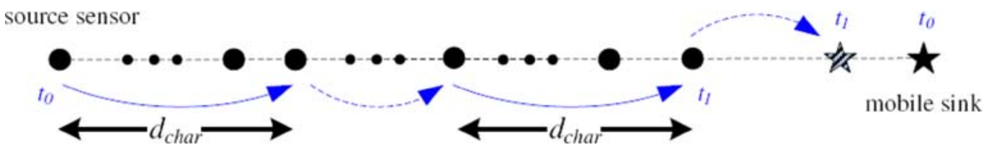

Figure 4. Energy efficient multihop clustering with consideration of message delivery deadline.

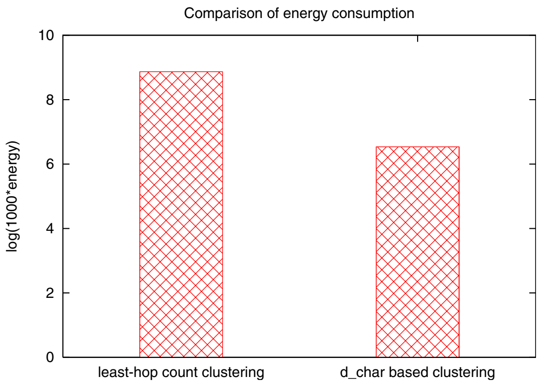

Figure 5. Energy consumption comparison between least-hop count clustering and d_{char} based multihop clustering schemes.

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 (i.e. sparse sensor networks), there may not exist sufficient relaying sensor nodes. In this case, sensor nodes have to wait until sink approaches and collect the buffered data. So, in next section, we turn to study the single-hop clustering scheme and the performance influence from sink mobility.

4. Performance Influence from Sink Mobility in Single-hop mWSN

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[1] probability" of packet transmission will rise. 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. Both sink and sensor nodes 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," 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 (i.i.d) random variables with common average of $\overline{Q}$. Consequently the epoch length of different L_is are also i.i.d random variables, sharing the same average of $\overline{L} = \overline{Q}v$.

Assume a stationary distribution of mobile sinks, in other words, 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 $\pi r^2 + 2rL_{i,k}$ during the k-th epoch (Figs. 5 and 6), 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 [34]), with the cumulative density function (cdf) as

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

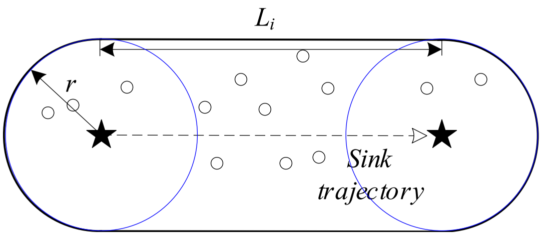

Figure 6. Illustration of computing the distribution of sensor-sink meeting delay.

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

$$F_X(x) = 1 - [1 - F_{X_i}(x)]^m \cong \sum_{x_k \leq x} mp(1-p)^{k-1}$$

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

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

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. However, the above analysis has implicitly neglected the time consumed by packet transmission during each sensor-sink encounters. 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

In case of packet segmentations, the split packets are assumed to be sent to different mobile sinks and reassembled. Message delivery delay can be mainly attributed to the packet transmission time, while the packet resequencing delay is out of the scope of our study. Assume each 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 $T=L/w$. Then with a service probability $p=m\pi r^2$, the service time of the message is a random variable with Pascal distribution (Lemma 1 of [6][2]). That is, the probability that the message can be transmitted within no more than x time slots, is

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

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

$$\overline{D_2} = \frac{1}{\lambda}\left[\rho + \frac{\rho^2 + \lambda^2\rho^2}{2(1-\rho)}\right]$$

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

$$\overline{D_2} = \frac{1}{\mu - 1} = \frac{1}{\frac{\pi mwr^2}{L} - 1}$$

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. One thousand five hundred sensor nodes have been deployed in a 10,000x10,000-m region. 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.

As can be found in Fig. 7, it coincides 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.

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

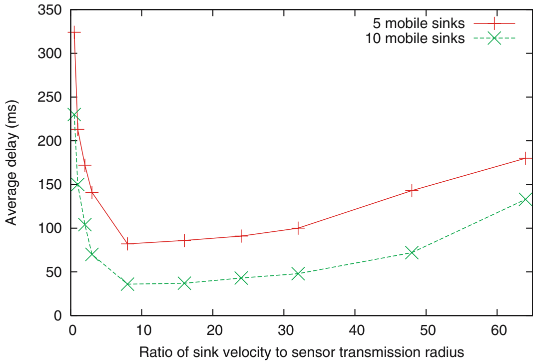

Figure 7. Average message delivery delay under different scenarios by varying the number and velocity of mobile sinks.

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=l/w), transmission range r, sink velocity v, and outage probability p_{outage}.

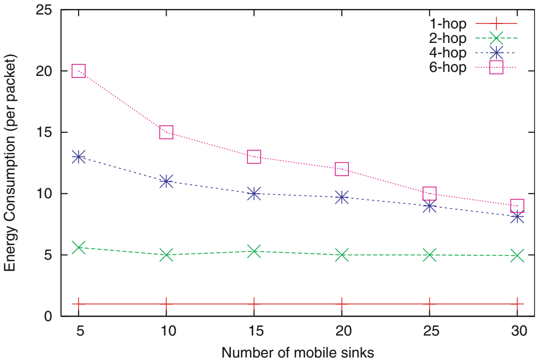

Figure 8. Average message delivery delay under different scenarios by varying the cluster size and member of mobile sinks.

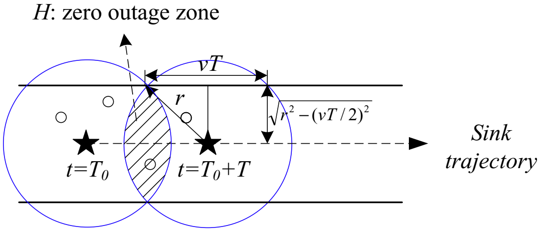

Figure 9. Illustration for computing the relationship between zero-outage probability and r, T.

Here we only 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.

Intuitively, if H is viewed as a queuing system, then the larger the area of H, the higher the service rate, thus the lower the average outage probability. 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). Therefore, the goal of enlarging the area of H can be achieved via increasing r, 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.

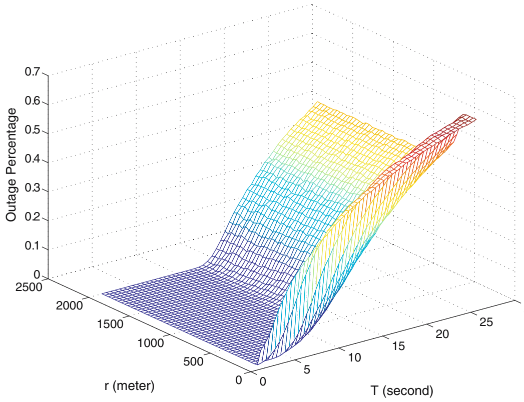

Figure 10. Outage probability vs. r and T.

Some preliminary simulation results can verify our expectations on the parameter tuning methods. With 3,000 sensor nodes and one mobile sink in a 10,000x10,000-m 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.

5. Conclusion

Mobile enabled 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. Our future work includes performance evaluation of mWSN under more realistic mobility models such as group based social mobility models.

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Notes

1. By *outage* we mean the incident of packet dropping after unsuccessful transmission due to the absence of reliable link with duration of a complete packet length between mobile sink and sensor node.
2. Assume the area of the sensor network is 1, and the service area of *m* mobile sinks is $1\text{-}(1-\pi r^2)^m \approx m\pi r^2$, therefore, the static service probability is approximately $m\pi r^2$. In fact, infinite sink velocity can lead to a service probability approaching 1.

Reference

1. I. F. Akyildiz, Weilian Su, Yogesh Sankarasubramaniam, and Erdal Cayirci, "A Survey on Sensor Networks," *IEEE Communications Magazine*, 2002 (August).
2. F. Ye, H. Luo, J. Cheng, and S.L.L. Zhang, "A Two Tier Data Dissemination Model for Large scale Wireless Sensor Networks," *Proc. of MOBICOM'02*, Atlanta, Georgia, USA, 2002, pp.148–159 (September 23–26).
3. R.C. Shah et al., "Data MULEs: Modeling a Three-tier Architecture for Sparse Sensor Networks," *Proc. of IEEE SPNA workshop*, 2003, pp. 30–41 (May 11).
4. S. Jain et al., "Exploiting Mobility for Energy Efficient Data Collection in Wireless Sensor Networks," *Mobile Networks and Applications*, vol. 11, no. 3, 2006, pp. 327–339 (June).
5. L. Tong, Q. Zhao, and S. Adireddy, "Sensor networks with mobile agents," *Proc. of IEEE MILCOM 2003*, Boston, MA, USA, 2003, pp.688–693 (October 13–16).
6. Y. Wang and H. Wu, "DFT-MSN: The Delay Fault Tolerant Mobile Sensor Network for Pervasive Information Gathering", *Proc. of IEEE INFOCOM'06*, Barcelona, Spain, 2006 (April 23–29).
7. B. Hull et al., "CarTel: A Distributed Mobile Sensor Computing System," *Proc. of ACM SenSys'06* (October 31–November 3).
8. W. Zhao, et al., "A Message Ferrying Approach for Data Delivery in Sparse Mobile Ad Hoc Networks," *Proc. of MobiHoc 2004*, Roppongi, Japan, 2004, pp. 187–198 (May 24–26).
9. W. Zhao et al., "Controlling the Mobility of Multiple Data Transport Ferries in a Delay-Tolerant Network," *Proc. of INFOCOM 2005*, Miami, Florida, USA, 2005, pp. 1407–1418 (March 13–17).
10. M.M.B. Tariq, et al., "Message Ferry Route Design for Sparse Ad hoc Networks with Mobile Nodes," *Proc. of MobiHoc 2006*, Florence, Italy, 2006, pp. 37–48 (May 22–25).
11. A.A. Somasundara, A. Ramamoorthy, and M. B. Srivastava, "Mobile Element Scheduling for Efficient Data Collection in Wireless Sensor Networks with Dynamic Deadlines," *Proc. of IEEE int'l Real-Time Sys. Symp.*, Lisbon, Portugal, 2004, pp. 296–305 (December 5–8).
12. E. Ekici et al., "Mobility-Based Communication in Wireless Sensor Networks," *IEEE Communications Magazine*, vol. 44, no. 7, 2006, pp. 56–62 (July).
13. A. Kansal et al., "Intelligent Fluid Infrastructure for Embedded Networks," *Proc. of MobiSys 2004*," Boston, Massachusetts, USA, 2004 pp. 111–124 (June 6–9).
14. D. Jea et al., "Multiple Controlled Mobile Elements (Data Mules) for Data Collection in Sensor Networks," *Proc. of DCOSS 2005*, Marina del Rey, CA, USA, 2005 (June 30–July 1).
15. A. Somasundara et al., "Controllably Mobile Infrastructure for Low Energy Embedded Networks," *IEEE Transactions on Mobile Computing*, vol. 5, no. 8, 2006, pp. 958–973 (August).

16. A. Chakrabarti et al., "Using Predictable Observer Mobility for Power Efficient Design of Sensor Networks," *Proc. of IPSN 2003*, Palo Alto, California, USA, 2003 (April 22–23).
17. H.S. Kim et al., "Minimum-Energy Asynchronous Dissemination to Mobile Sinks inWireless Sensor Networks," *Proc. of SenSys 2003*, Los Angeles, California, USA, 2003, pp. 193–204 (November 5–7).
18. K. Akkaya and M. Younis, "Energy-aware Routing to a Mobile Gateway in Wireless Sensor Networks," *Proc. of Globecom 2004*, Dallas, Texas, USA, 2004, pp.16–21 (November 29–December 3).
19. P. Baruah and R. Urgaonkar, "Learning-Enforced Time Domain Routing to Mobile Sinks in Wireless Sensor Fields," *Proc. of LCN 2004*, Tampa, Florida, 2004 (November 16–18).
20. J. Luo and J.-P. Hubaux, "Joint Mobility and Routing for Lifetime Elongation in Wireless Sensor Networks," *Proc. of INFOCOM 2005*, Miami, USA, 2005, pp. 1735–1746 (March 13–17).
21. J. Luo et al., "MobiRoute: Routing towards a Mobile Sink for Improving Lifetime in Sensor Networks," *Proc. of DCOSS 2006*, San Francisco, CA, USA, 2006 (June 18–20).
22. S.R.Grandham et al., "Energy Efficient Schemes for Wireless Sensor Networks with Multiple Mobile Base Stations," *Proc. of IEEE Globecom 2003*, San Francisco, CA, USA, 2003, pp. 377–381 (December 1–5).
23. Z.M. Wang et al., "Exploiting Sink Mobility for Maximizing Sensor Networks Lifetime," *Proc. of HICSS 2005*, Hawaii, 2005 (January 3–6).
24. W. Wang et al., "Using Mobile Relays to Prolong the Lifetime of Wireless Sensor Networks," *Proc. of MobiCom 2005*, Cologne, Germany, 2005, pp. 270–283 (August 28 – September 2).
25. Y.T. Hou et al., "Prolonging Sensor Network Lifetime with Energy Provisioning and Relay Node Placement," *Proc. of SECON 2005*, Santa Clara, California, USA, 2005 (September 26–29).
26. S. Eidenbenz et al., "Maneuverable Relays to Improve Energy Efficiency in Sensor Networks," *Proc. of PerCom 2005 Workshops*, Hawaii, 2005, pp. 411–417, (March 8–12).
27. Z. Vincze et al., "Adaptive Sink Mobility in Event-driven Multihop Wireless Sensor Networks," *Proc. of InterSense 2006*, Nice, France, 2006 (May 30–31).
28. L. Sun, Y. Bi, and J. Ma, "A Moving Strategy for Mobile Sinks in Wireless Sensor Networks," *Proc. of IEEE SECON'06 (poster)*, Reston, VA, USA, 2006 (September 25–28).
29. B. Ren, J. Ma, and C. Chen, "The Hybrid Mobile Wireless Sensor Networks for Data Gathering," *Proc. of Int'l Wireless Communications and Mobile Computing Conference (IWCMC'06)*, Vancouver, Canada, 2006 pp. 1085–1090 (July 3–6).
30. C. Chen, J. Ma, and K. Yu, "Designing Energy Efficient Wireless Sensor Networks with Mobile Sinks," *Proc. of ACM Sensys'06 Workshop WSW*, Boulder, Colorado, 2006, USA (October 31).
31. S. Bandyopadhyay and E.J. Coyle, "An energy efficient hierarchical clustering algorithm for wireless sensor networks," *Proc. of IEEE INFOCOM*, San Francisco, CA, 2003, pp. 1713–1723 (March 30–April 3).
32. H.M. Ammari and S.K. Das, "Trade-off between Energy Savings and Source-to-Sink Delay in Data Dissemination for Wireless Sensor Networks," *Proc. of MSWiM'05*, Montreal, Quebec, Canada, 2005, pp. 126–133 (October 10–13).
33. M. Haenggi and D. Puccinelli, "Routing in Ad Hoc Networks: A Case for Long Hops," *IEEE Commun Mag*, vol. 43, no. 10, 2005, pp. 93–101 (October).
34. T. Spyropoulos et al., "Performance Analysis of Mobility-assisted Routing," *Proc. of ACM MobiHoc'06*, Florence, Italy, 2006, pp. 49–60 (May 22–25).

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