# Query-Based Data Collection in Wireless Sensor Networks with Mobile Sinks [*]

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## ABSTRACT

Considering sensor nodes deployed densely and uniformly in the sensing field, we focus on a scenario that a mobile sink moving through the sensing field queries a specific area or a point of interest for data collection. A *Query* packet is injected by the mobile sink and routed to the specific area, then the corresponding *Response* packet is returned to the mobile sink via multi-hop communication. Due to the mobility of the sink, the *Query* and *Response* should have different routes. We analyze such a network model to address the problem of efficient data collection in wireless sensor networks and propose an efficient Query-Based Data Collection Scheme (QBDCS). In order to minimize the energy consumption and packet delivery latency, QBDCS chooses the optimal time to send the *Query* packet and tailors the routing mechanism for partial sensor nodes forwarding packets. Simulation results demonstrate that QBDCS completes a query-based data collection cycle with minimum energy consumption and delivery latency.

## Categories and Subject Descriptors

C.2.1 [**Computer-Communication Network**]: Network Architecture and Design—*Wireless communication*

## General Terms

Algorithms, Design

## Keywords

Wireless sensor networks; Mobile sinks; Query-based data collection

## 1. INTRODUCTION

Recently, Wireless Sensor Networks (WSNs) have been designed and developed in many application areas, such as monitoring physical environments, habitat monitoring, health care, and traffic surveillance applications [1].

Sensors usually operate on limited non-rechargeable battery power and are expected to run for a long time. Thus, the problem of energy efficient data collection becomes one of the substantial issues in WSNs. Aiming at solving this problem, researchers have proposed to exploit mobility of sinks for energy efficient data collection in WSNs [2]. This can balance the energy consumption of each sensor node and reduce the possibility of "routing hotspots", which are introduced by fixed sinks due to the nearby heavy data flow.

Employing existing mobile devices such as mobile handsets and vehicles as sinks for data collection is proposed in MULEs[3] TSA-MSSN[4] and [5], etc. Although their mobility is considered random, during a short period, in most situations they would follow certain mobility models and their future position can thus be predicted based on the continuity of mobility. For example, when a vehicle moves along the road and the digital map is available, the prediction of its future mobility becomes much accurate.

In this paper, we focus our investigation on densely and uniformly deployed WSNs, and a mobile sink moving at a certain speed through the sensing field querying a specific area or a point of interest to collect sensed data. We analyze such a network model to address the problem of efficient data collection in WSNs. To solve this problem, position prediction technique is adopted in this paper. Our specific contribution mainly comes from the proposed efficient Query-Based Data Collection Scheme (QBDCS). QBDCS finds the optimal time to inject the *Query* packet, so as to complete a query-based data collection cycle with minimum energy consumption and delivery delay.

The rest of this paper is organized as follows: Section 2 surveys the related works. Section 3 presents the system model. In Section 4, we provide detailed design description of QBDCS. In Section 5, we conduct a simulation study of QBDCS. Finally, Section 6 concludes this paper.

## 2. RELATED WORKS

The problem of efficient data collection in WSNs has been intensively investigated. Most researches are based on the assumption that data collection involves all nodes of a WSN. A typical representative is the LEACH protocol [6]. How-

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ever, there is a number of queries that select only a subset of the nodes in a network [7]. Upon receiving a user's query message, each sensor node that is corresponding to the query delivers the sensed data to the sink node. In [8], an on-demand localized data collection scheme is proposed. In contrast to the sink with fixed position in [8], we focus on the query-based data collection with mobile sinks.

In [9], the authors propose an adaptive routing algorithm based on the instantaneous position estimation to route the *Response* packet. However, the routing path of *Response* in [9], which is expected to be an arc line theoretically, deviates from the optimum. It's because that each relaying sensor node estimates the instantaneous mobile sink position and then routes the *Response* towards that position in their method, unlike QBDCS forwarding the *Response* towards the predicted packet-sink meeting position directly. Besides, the work [9] only considers the Response Propagation phase, while we consider a complete query-based data collection cycle, including choosing the right moment to inject the *Query* packet.

# 3. SYSTEM MODEL

## 3.1 Assumptions

We make the following common and reasonable assumptions for our network model:

- Sensor nodes are homogeneous, energy-constraint, immobile and expected to run for a long time. They are able to wirelessly communicate with neighbors in a short range.
- Each sensor node has a duty cycle $D_C \in [1\%, 100\%]$. It periodically opens the radio to transmit sensed data, but in other time it sleeps to save energy.
- Each sensor node can identify its geographic location and maintains a neighbor table for routing packets. The location information can be gained by running a localization algorithm [10].
- The mobile sink has an estimation of its current mobility (velocity, direction and position), which can be obtained from the GPS, etc. It operates on a rechargeable battery and has much higher computation and communication capabilities than sensor nodes.
- The mobile sink can obtain the sensor node's information, such as transmission range, duty cycle. This can be achieved by the initial negotiation procedure.

## 3.2 Network model

Our network model consists of three tiers: Sensor nodes, On-demand cluster head and Mobile sink. By sending a *Query* packet to a WSN, the mobile sink queries a specific area or a point of interest for sensed data in the sensing field, where sensor nodes are densely and uniformly deployed. Each *Query* packet includes the location information of the interested area. The sensor node closest to the center of the interested area elects itself as the cluster head, which we call an "on-demand cluster head", and is responsible for gathering and aggregating the data in the interested area. The aggregated data (*Response* packet) is then sent back to the mobile sink via multi-hop communication. As shown in Figure 1, a vehicle is moving along a straight road, and queries a WSN deployed around the road. Such networks are appropriate for either environmental monitoring applications or the Intelligent Transportation Systems (ITS) [11], where the deployed WSNs enable vehicles to obtain the conditions of the surrounding environment, e.g., the status of parking slots along the street.

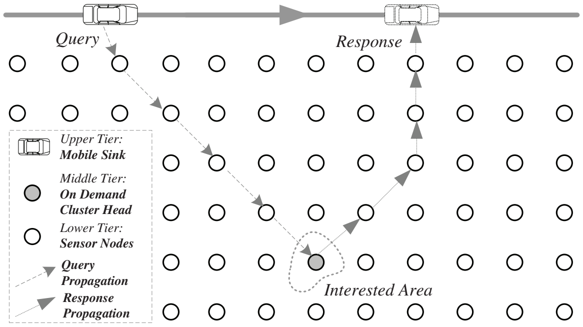

**Figure 1: Query-based data collection in WSNs with mobile sinks**

## 3.3 Problem formulation

A complete query-based data collection cycle is composed by three phases: 1) Query Propagation phase; 2) Data Aggregation phase; 3) The subsequent Response Propagation phase. QBDCS mainly customizes the routing mechanism for sensor nodes forwarding the *Query* and *Response* packets. In this paper, the Data Aggregation phase is not emphasized.

The QBDCS problem is conceptually formulated by the following question: how can the WSNs complete transmission of the *Query* and *Response* packets with minimum energy consumption and delivery latency? The basic technique we adopt is the geographical location aware routing.

To minimize the energy consumption and delivery latency to transmit the *Query* and *Response* packets, we take the following specific approaches. 1) We estimate the packet delivery velocity and predict the position of the mobile sink at the time it meets the *Response* packet. Thus, the *Response* packet can be forwarded towards the meeting position via multi-hop wireless transmission directly with geographical location aware routing. 2) We find the optimal time for the mobile sink to inject the *Query* packet to a WSN.

# 4. QBDCS DESIGN

## 4.1 Packet delivery velocity estimation

The packet delivery velocity $V$ is defined as the delivered distance a packet travels divided by its end-to-end delay [12]. Let $L$ be the length of the packet; $R$ be the data transmission rate of each sensor node; $d$ be the distance between data source and destination; and $r$ be the communication range of each sensor node. Let $d_{hop}$ be the average distance per hop ($d_{hop} \leq r$). The number of hops between a source and destination is roughly linear with the distance $d$ between the source and the destination locations, and the variance depends on the actual WSNs deployment. Taking the duty cycled $D_C$ operation into account by introducing an additional delay to each packet transmission, we have the estimated packet delivery velocity,

$$V = \frac{d}{\frac{L}{R\cdot D_C}\cdot\lceil\frac{d}{d_{hop}}\rceil} \approx \gamma\cdot\frac{r\cdot R\cdot D_C}{L}, \quad 0<\gamma\le 1 \tag{1}$$

$\gamma$ ($\gamma = \frac{d_{hop}}{r}$) is the modification coefficient in the packet delivery velocity estimation by taking into account the actual deployment of sensor nodes.

## 4.2 Meeting position prediction

The *Query* packet is composed of the following elements:

- Interested types of the sensed data (temperature, humidity, etc.)
- Geographic location information of the interested sensing field (radius and center)
- Mobile sink mobility status and the timestamp
- Routing hop counts.

Let $t_0$ denote the query time point and $t_1$ denote the time point that the corresponding *Response* will be sent; $L_r$ be the length of the *Response* packet; $V_r$ be the estimated delivery velocity of the *Response* packet. Given the starting point $(x_1, 0)$ of the *Query* packet, the center of the interested sensing area $(a, b)$ and the velocity of mobile sink $V_s$, as depicted in Figure 2, we have the estimated meeting position $(x_2, 0)$ of the packet and mobile sink.

$$(t_1 - t_0) + \frac{\sqrt{(x_2-a)^2+b^2}}{V_r} = \frac{|x_2 - x_1|}{V_s} \tag{2}$$

where $V_r = \gamma\cdot\frac{r\cdot R\cdot D_C}{L_r}$.

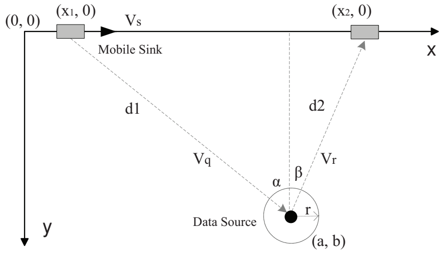

**Figure 2: Packet and mobile sink meeting position estimation**

## 4.3 Meeting position aware routing

Meeting Position Aware Routing (MPAR) is designed for forwarding the *Response* packets in Response Propagation phase. It predicts the meeting position of the *Response* packet and mobile sink. Thus the requested data can be directionally propagated towards the mobile sink. It is also a scalable protocol for that it makes forwarding decisions based on one-hop neighborhood information, which enables MPAR to scale effectively to large scale WSNs.

### 4.3.1 Chasing mode

We call the sensor node nearest to the estimated meeting position as the "notifying node". When the *Response* packet arrives at the "notifying node" and finds that the mobile sink has not passed and is not in its radio range, the "notifying node" waits for the mobile sink to come and then delivers the packet. However, it is possible that by the time the *Response* packet arrives at the "notifying node", the mobile sink has already passed, when the mobile sink's mobility varies significantly. In this case, the "notifying node" enters into the Chasing Mode, in which the *Response* packet chases the mobile sink along the road.

### 4.3.2 Deadline awareness

In order to avoid the case that the packet chases the mobile sink endlessly, there usually exists a limit ($T_{deadline}$) on the period of propagation time that the user allows between sending out the *Query* and receiving the *Response* packet. If the *Response* packet can not arrive at the destination within $T_{deadline}$, it should be discarded.

## 4.4 Optimal query time

Let $E_q$ and $E_r$ be the average energy consumption for transmitting the *Query* and *Response* packets per hop respectively; $L_q$ be the length of the *Query* packet; $V_q$ be the estimated delivery velocity of the *Query* packet. The two objectives of QBDCS are to minimize the energy consumption and the delivery latency when transmitting the *Query* and the corresponding *Response* packets. These two objectives are inherently unified. Thus, we choose minimizing energy consumption as the QBDCS objective. The optimization problem can be formulated as following,

$$\min\{E_q\cdot\frac{\sqrt{(x_1-a)^2+b^2}}{d_{hop}} + E_r\cdot\frac{\sqrt{(x_2-a)^2+b^2}}{d_{hop}}\} \tag{3}$$

where $E_q = P_t\cdot\frac{L_q}{R}$ and $E_r = P_t\cdot\frac{L_r}{R}$. $P_t$ denotes the transmission power of a packet. The constraint condition is

$$\frac{\sqrt{(x_1-a)^2+b^2}}{V_q} + t_g + \frac{\sqrt{(x_2-a)^2+b^2}}{V_r} = \frac{|x_2-x_1|}{V_s} \tag{4}$$

where $V_q = \gamma\cdot\frac{r\cdot R\cdot D_C}{L_q}$ and $V_r = \gamma\cdot\frac{r\cdot R\cdot D_C}{L_r}$. $t_g$ is the estimated data aggregation time in the interested sensing area, which is proportional to the size of the interested area.

Lagrangian Multiplier method is applied to solve this problem. Incorporating the condition into Formula.5, we have the auxiliary function

$$\begin{aligned} L(x_1, x_2, \lambda) = E_q\cdot\frac{\sqrt{(x_1-a)^2+b^2}}{d_{hop}} + E_r\cdot\frac{\sqrt{(x_2-a)^2+b^2}}{d_{hop}} + \\ \lambda\cdot\{\frac{\sqrt{(x_1-a)^2+b^2}}{V_q} + \frac{\sqrt{(x_2-a)^2+b^2}}{V_r} + t_g - \frac{|x_2-x_1|}{V_s}\}, \end{aligned} \tag{5}$$

and solve

$$\bigtriangledown_{x_1, x_2, \lambda} L(x_1, x_2, \lambda) = 0 \tag{6}$$

When the mobile sink is located at the critical point $(x_1, 0)$, where the objective function attains a global minimum, we get the optimal query time which can minimize the energy consumption and delivery latency when transmitting the *Query* and *Response* packets.

CLAIM 1. *The theoretical optimal query time depends on the ratio of the packet length of Response and Query (*$\frac{L_r}{L_q}$*). As shown in Figure 3, when* $\frac{L_r}{L_q} > 1$*, the optimal query time is when the mobile sink can just meet the Response packet at* $(a, 0)$*. When* $\frac{L_r}{L_q} < 1$*, the optimal query time is just when the mobile sink located at* $(a, 0)$*.*

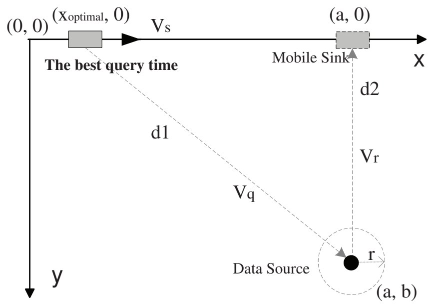

**Figure 3: Theoretical optimal query time based on meeting position aware routing when $\frac{L_r}{L_q} > 1$**

Proof. *let $\frac{L_r}{L_q} = k$, we have $\frac{E_r}{E_q} = k$, $\frac{V_r}{V_q} = \frac{1}{k}$. To simplify the analysis, we assume $t_g \approx 0$, which will not affect the final result. The objective function can be written as*

$$\frac{E_q}{d_{hop}} \cdot \min\{d_1 + k \cdot d_2\}, \tag{7}$$

*where $\frac{E_q}{d_{hop}}$ can be regarded as a constant. Let $\frac{V_q}{V_s} = m$, the constraint is*

$$d_1 + k \cdot d_2 = m \cdot (\sqrt{d_1^2 - b^2} + \sqrt{d_2^2 - b^2}). \tag{8}$$

*Applying Lagrange Multipliers method yields*

$$\begin{cases} k \cdot \frac{d_1}{\sqrt{d_1^2-b^2}} - \frac{d_2}{\sqrt{d_2^2-b^2}} = 0 \\ d_1 + k \cdot d_2 - m \cdot (\sqrt{d_1^2 - b^2} + \sqrt{d_2^2 - b^2}) = 0. \end{cases} \tag{9}$$

*Let $d_1 = b \sec\alpha$ and $d_2 = b \sec\beta$, $\alpha, \beta \in (0, \frac{\pi}{2})$. Equations.(9) can be written as*

$$\begin{cases} \frac{k}{\sin\alpha} - \frac{1}{\sin\beta} = 0 \\ \sec\alpha + k\sec\beta - m\tan\alpha - m\tan\beta = 0, \end{cases} \tag{10}$$

*which has boundary values when $\alpha = 0$ or $\beta = 0$. Solving the Equations.(10), when $k \neq 1$, we have*

$$-2mk\sin^3\beta + (m^2 + k^2 + 1)\sin^2\beta = 0. \tag{11}$$

*Thus,*

$$\sin\beta = \frac{m^2+k^2+1}{2mk} \qquad \beta \in (0, \tfrac{\pi}{2}). \tag{12}$$

*Obviously, Equation.(12) has no solution. Therefore, the objective function attains the optimal value when $\alpha = 0$ or $\beta = 0$. When $k > 1$, it can be proven that the objective function has optimal value when $\beta = 0$, which is equivalent to the mobile sink and Response packet meeting at $(a, 0)$.* □

Based on the above analysis, when the *Query* packet is shorter than the *Response* packet in length, QBDCS finds the optimal query time when the mobile sink is located at $(x_{optimal}, 0)$, where

$$\frac{\sqrt{(a - x_{optimal})^2 + b^2}}{V_q} + t_g + \frac{b}{V_r} - \frac{a - x_{optimal}}{V_s} = 0. \tag{13}$$

## 4.5 Summary of QBDCS

The Query-Based Data Collection Scheme is summarized in Table. 1.

**Table 1: Summary of the QBDCS in WSNs with mobile sinks**

**Given** $V_s, R, r, L_q, L_r, D_C, (a, b), d_{hop}$.
**Calculate** The optimal query time $(X_{optimal}, 0)$ **by** Equation.(13) and the estimated meeting position.

**Step 1: Querying at the right time.**
The mobile sink checks whether it is at the optimal query time. If yes, then it injects the *Query* packet towards the interested area.
**Step 2: Routing the Query packet.**
The *Query* is routed towards the interested area by adopting the geographical location aware routing.
**Step 3: Data aggregation.**
Once the *Query* packet arrives at the targeted sensing area, the sensor node closest to the center of the interested sensing area elects itself as the cluster head and is responsible for gathering and aggregating the sensor data.
**Step 4: Routing the Response packet.**
The *Response* packet is then routed towards the mobile sink (estimated meeting position) until it arrives at the sensor node nearest to the estimated meeting position, which we call the "notifying node". The "notifying node" checks whether the mobile sink has passed and is not in the sensor node's radio range. If has not passed, the "notifying node" waits for the mobile sink to enter its radio range before delivering the *Response* packet. If has passed, the *Response* packet enters into the Chasing Mode until it catches up with the mobile sink. During this process, if exceeding the time limit $T_{deadline}$, the *Response* packet should be discarded.
**Step 5: Response packet delivery.**
The *Response* packet is delivered to the mobile sink.

# 5. EVALUATION

To evaluate the performance of the proposed QBDCS, we simulate an application scenario where sensor nodes are deployed in the sensing field densely and uniformly, using the simulation tool OMNeT++ [13]. We generate a rectangular grid with 50 × 20 cells. The side length of each cell is 30m. The mobile sink is moving on a straight road with a certain speed and may query an arbitrary interested area in the sensor deployed field.

We define the vertical distance from the interested area to the road where the mobile sink is moving along as Query Distance (QD). For comparison, we also simulate the "Naive" scheme, which the mobile sink sends the *Query* when locating at the nearest point from the interested area, as shown in Figure 4. Assume both of them adopt the MPAR protocol to forward the *Response* packet. The simulation starts from the mobile sink injecting a *Query* packet towards the interested area, and ends when mobile sink receives the *Response* packet.

## 5.1 Performance metric

### 5.1.1 Delivery Latency

Delivery Latency is defined as the amount of time from

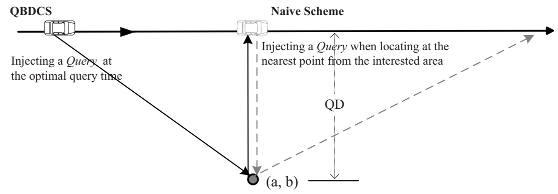

**Figure 4: Schematic of the routing paths in QBDCS and the "Naive" scheme under ideal condition**

injecting a *Query* packet by the mobile sink to the corresponding *Response* packet returning to the mobile sink. In QBDCS, the energy consumed in a WSN for transmitting a packet is proportional to its hop counts, which is also the determinant of the delivery latency. Minimizing the delivery latency and energy consumption in QBDCS are inherently unified. As a representative, the Delivery Latency is used as a performance metric in our simulation.

## 5.2 Simulation settings

The key communication parameters generally applies to IEEE 802.15.4. The velocity of mobile sinks varies from $20m/s$ to $30m/s$. For simplicity, we assume the data aggregation time $t_g = 1$ s. The data transmission rate $R$ is taken $250kb/s$, sensor transmission range $r$ is taken $50m$. $CSMA/CA$ mechanism for collision management is adopted. Taking data-link layer $CSMA/CA$ mechanism into consideration, about 40% overhead is introduced [9]. Thus, the data transmission rate under saturation condition is $R' = 150kb/s$. Sensor nodes have a cycle time $C_T = 1s$, $D_C = 1\%$. Assume the *Query* and *Response* packets length are $L_q = 50$ bytes and $L_r = 127$ bytes respectively. Therefore, the estimated delivery velocity $V_q$ ($V_q = \gamma \cdot \frac{r \cdot R' \cdot D_C}{L_q}$) and $V_r$ ($V_r = \gamma \cdot \frac{r \cdot R' \cdot D_C}{L_r}$) are $187.5 \cdot \gamma\ m/s$ and $73.8 \cdot \gamma\ m/s$. Let $D_q$ and $D_r$ denote the maximum delay of the *Query* and *Response* packets respectively. We have $D_q \approx 267\ ms$ and $D_r \approx 677\ ms$.

## 5.3 Simulation results

### 5.3.1 Choosing the modification coefficient $\gamma$

The estimation of packet delivery velocity has direct effect on the performance of QBDCS. We simulate a mobile sink querying the area with Query Distance $QD = 510\ m$. From Figure 5, it is shown that the optimal value for the modification coefficient $\gamma$ is around 0.7, at which the QBDCS shows the least delivery latency.

Figure 6 depicts the change of the *Query* and *Response* hop-count in a query-based data collection cycle by increasing the value of $\gamma$ when $V_s = 30m/s$. When $\gamma$ is underestimated (smaller than 0.7), it results in sending *Query* packet earlier than the optimal query time. Thus, the *Query* hop-count is more than the *Response* hop-count. In this case, the *Response* packet will arrive at the "notifying node" in advance and wait for the mobile sink, which increases the delivery latency. When $\gamma$ is overestimated (larger than 0.7), it leads to sending *Query* packet later than the optimal query time. When the *Response* packet arrives at the "notifying node", the mobile sink has already passed. The *Response* packet has to enter into the Chasing Mode, which increases both the delivery latency and energy consumption. This is the reason that the *Response* hop-count is more than the *Query* hop-count when $\gamma$ is overestimated.

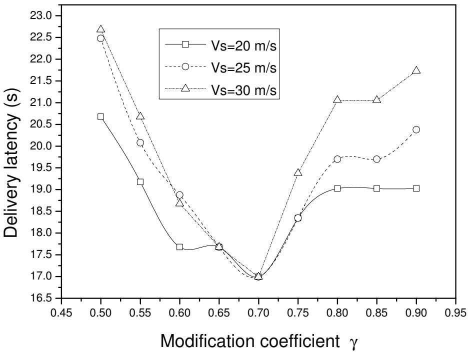

**Figure 5: The dependance of delivery latency on the modification coefficient $\gamma$ in QBDCS**

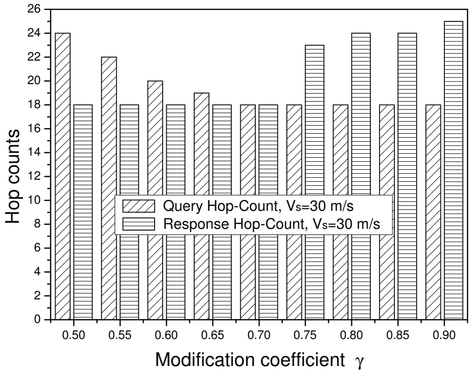

**Figure 6: The change of packet hop counts by increasing the value of $\gamma$ in QBDCS**

It is found that the optimal value of the modification coefficient $\gamma$ depends on the sensor deployment strategy. As in our simulation, where sensor nodes are deployed in the sensing field densely and uniformly, forming a two dimensional grid, the optimal value of $\gamma$ is about 0.7.

### 5.3.2 The impact of mobile sink velocity

We set the Query Distance to be $510m$, and vary the mobile sink velocity from $20m/s$ to $30m/s$. The modification coefficient $\gamma$ is taken 0.7. Figure 7 depicts the effect of increasing mobile sink velocity on the delivery latency.

As shown in Figure 7, QBDCS is insensitive to the variance of the mobile sink velocity. With the increase of the mobile sink velocity, the "Naive" scheme pays more cost. This is because that delivery latency of completing a query-based data collection cycle mainly depends on the hop counts of routing the *Response* packet. QBDCS can assure the least hop-count during the Response Propagation phase.

### 5.3.3 The impact of query distance

We vary this distance from $120m$ to $510m$, to compare the differences when mobile sink velocity is set $25m/s$ and $30m/s$ respectively. The modification coefficient $\gamma$ is taken 0.7. Obviously, the delivery latency and energy consump-

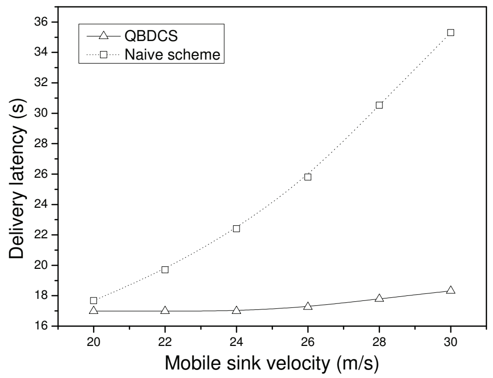

**Figure 7: Delivery Latency vs. mobile sink velocity**

tion depend on the Query Distance (QD). The longer Query Distance, the larger delivery delay and more energy consumption.

As shown in Figure 8, with an increase of the Query Distance, the advantage of QBDCS becomes more significant. It is notable that the increasing speed of the delivery latency in QBDCS almost keeps consistent when $V_s = 25m/s$ and $V_s = 30m/s$. For the "Naive" scheme, however, the increasing speed of the delivery latency increases as the mobile sink velocity increases.

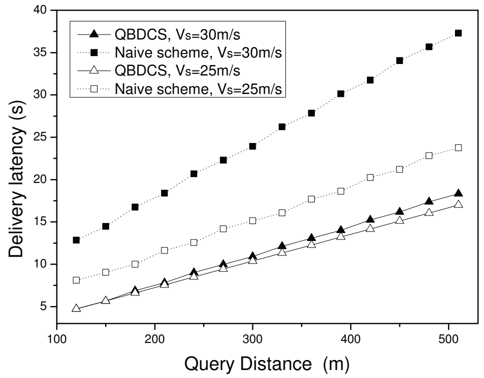

**Figure 8: Delivery Latency vs. Query Distance**

## 5.4 Discussion

In our simulation, we consider the general conditions when $D_C = 1\%$. Although QBDCS will be close to the "Naive" scheme when duty cycle $D_C$ is large enough or the mobile sink velocity is slow enough, which means that the estimated delivery velocity of a packet is much larger than the mobile sink velocity, QBDCS will not be worse than the "Naive" scheme.

# 6. CONCLUSION

In this paper, we addressed the problem of query-based data collection in WSNs with mobile sinks. We estimated the packet delivery velocity and predicted the packet-sink meeting position. Then, we proposed an efficient Query-Based Data Collection Scheme (QBDCS), as the main contribution of this paper. QBDCS chooses the optimal query time to send the *Query* packet and tailors the routing mechanism for partial node participation in a WSN. Through theoretical analysis and simulations, we illustrated that QBDCS can achieve minimization of the energy consumption and delivery latency in a query-based data collection cycle.

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