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A Model-Aided Data Gathering Approach for Wireless Sensor Networks*

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How to collect data energy-efficiently from sensor nodes is an important research issue in wireless sensor networks. In this paper, we address the problem of gathering data from sensor nodes using a model-aided data gathering approach. In our approach, a model is maintained by a node and a replica of the model is maintained the base station. The base station uses the replica model to estimate the actual measurement data of the sensor node in usual time, and an actual measurement datum is sent to the base station only when the error of the model's corresponding estimation exceeds allowable error bound. In such a way, energy can be saved by reducing the transmission of actual measurement data. Experimental results show the effectiveness of our approach.

Keywords: wireless sensor networks, model-aided, data gathering, energy efficient, data fitting

1. INTRODUCTION

With the rapid advancement in wireless communications technology and micro-electro-mechanical systems (MEMS) technology, the wide deployment of large-scale wireless sensor networks (WSNs) has been made possible. Due to their features of reliability, accuracy, flexibility, cost-effectiveness and ease of deployment, WSNs are promising to be used in a wide range of applications, such as environmental monitoring, health monitoring and target tracking [1], *etc*. As a result, wireless sensor networks have been attracting increasing research interest.

Wireless sensor networks can offer us revolutionary new methods of accessing data from real environment [2]. However, because of the limited power of sensor nodes, gathering data is still a challenging work. For example, a Berkeley mote is only powered by two alkaline AA batteries [3]. Furthermore, it is infeasible to replenish the energy of sensor nodes by replacing the batteries in many applications. Therefore, data gathering approaches of high energy-efficiency are strongly needed.

Motivated by the need of extending the network lifetime of energy-constrained wireless sensor networks, there has been considerable research in the area of energy-efficient data gathering in sensor networks and many techniques [4-10] have been proposed and developed. Among these techniques in-network aggregation and compression are two noticeable techniques. Although the measures they take are different, they are both trying to save energy by reducing the total amount of data transmitted.

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Aggregation [4] is an in-network query processing technique for wireless sensor networks. By such a technique, for an aggregation query (*e.g.*, the average rainfall of the monitored area), sensor readings are accumulated into partial results as the data messages propagate toward the base station. TinyDB [5] and Cougar [6] are two examples of utilizing aggregation to reduce energy consumption. On the other hand, compression attempts to take advantage of the correlation in the data and exploit coding techniques to reduce the size of data transmitted. For example, in [7], Ganesan *et al*. use wavelet based approach to compress the sensor data; while in [8] Chou *et al*. use distributed source coding to reduce the redundancy of the data to be transmitted to the sink.

However, both in aggregation and compression, all sensor nodes still need to transmit their data to the base station. In this paper, we propose a model-aided data gathering approach for wireless sensor networks. In our approach, a predictive model M_i is maintained by a sensor node N_i and an identical model M_i' is maintained by the base station. The base station utilizes M_i' to estimate the actual measurement data of node N_i. At the same time, M_i is used by node N_i to judge how the estimations of model M_i agree with the actual measurement data. A measurement datum will be reported to the base station only when the error of corresponding estimative figure exceeds allowable error bound. In such a way, communication cost can be reduced and measurement error can be controlled in an allowable range. Our approach can be used in combination with aggregation and compression to increase energy reduction.

The rest of this paper is organized as follows. In section 2, we give the WSN model on which our research are based and present an overview of our approach. In section 3, we discuss our approach in detail. In section 4, the implementation issues are discussed. Experimental results are presented in section 5 to show the effectiveness of our approach. We conclude in section 6.

2. NETWORK MODEL AND OVERVIEW OF APPROACH

In this paper, we consider wireless sensor networks that are deployed for monitoring applications. Examples of such kind of applications include environmental monitoring, health monitoring of human body or buildings, agriculture monitoring, *etc.* [1]. In these applications, sensor nodes are required to continuously sense the monitored phenomena and send the sensed data to the base station for further processing [11].

2.1 Wireless Sensor Network Model

Without loss of generality, the network model used in this paper is based on following assumptions:

1) A wireless sensor network *WSN* is deployed to monitor a phenomenon *PH*. *WSN* is composed of a base station *BS* and a set of sensor nodes $\{N_1, N_2, \ldots, N_n\}$. N_i is a unique identifier assigned to node i.
2) Sensor nodes are energy-constrained; while base station *BS* is not energy-constrained.
3) A sensor node N_i senses *PH* periodically at a fixed frequency f. A datum X_i^t is measured by N_i at a measurement time instant t.

4) Time is synchronized between sensor nodes and the base station using certain techniques [12].
5) The communication is reliable and there is no data loss happens when the packets are being transmitted to *BS* [13].

2.2 Overview of Approach

We give an overview of our approach using an example of monitoring the blood pressure of patients in a hospital. Fig. 1 gives how the blood pressure of hypertension patients changes in 24 hours [14]. DBP and SBP denote diastolic blood pressure and systolic blood pressure, while SH and EH represent secondary hypertension and essential hypertension. As the figure shows, the blood pressure does not change desultorily. On the contrary, it fluctuates cyclically (with a period of 24 hours). The blood pressure changes continuously and it reaches its highest and lowest points at approximately 8 o'clock AM and 2 o'clock PM. Our approach uses these rules to achieve its energy-efficiency.

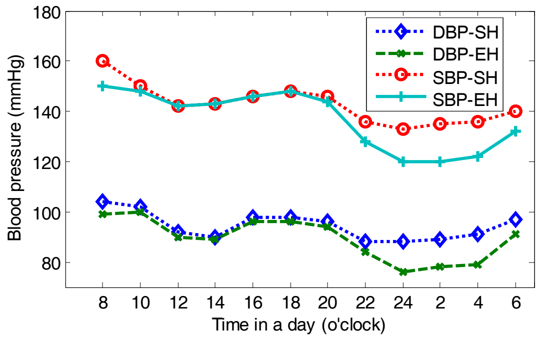

Fig. 1. Blood pressure curve in 24 hours [14].

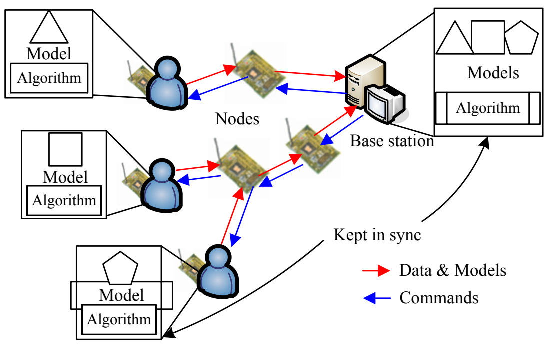

Fig. 2. Overview of approach.

Fig. 2 gives an overview of our approach. The base station uses commands to request the sensor nodes to sense the patients' blood pressure for a period of time *T* and at a certain frequency f, with an error bound ε is allowed. As the figure shows, a pair of models is maintained, with one model M_i distributed on node N_i and the other M_i' on BS. M_i and M_i' are always kept in synchronization. Model M_i is induced by a light-weight algorithm running on N_i from the measurement data set. Assume at a time instant t, a copy M_i' of M_i is sent to BS. Then at next time instant $t + 1$, BS can utilize model M_i' to estimate the actual measurement data of the sensor node N_i. At the same time, N_i still measures the blood pressure and compares the estimation E_i^{t+1} of M_i with the actual measurement data X_i^{t+1}. If $|E_i^{t+1} - X_i^{t+1}| \leq \varepsilon$ (ε is the allowable error bound), the measurement data X_i^{t+1} is not reported to BS, otherwise X_i^{t+1} is reported to BS.

3. PRINCIPLE OF APPROACH

3.1 Predictability of Phenomena

The changes of natural phenomena follow some temporal and spatial rules. In this paper we focus on the temporal rules of the changing processes of physical phenomena. One temporal rule is that the changing process of a phenomenon may consist of gradual phases and abrupt phases. An example is the air temperature in a garden. The air temperature may change rapidly and violently in a short time, yet in most of the time it changes slowly and smoothly. Fig. 3 shows a changing process that has gradual phases: P_{g1}, P_{g2}, P_{g3}, and abrupt phases: P_{a1} and P_{a2}. During a gradual phase, the state of the phenomenon changes gradually and continuously; while the state of the phenomenon changes rapidly and discontinuously during an abrupt phase.

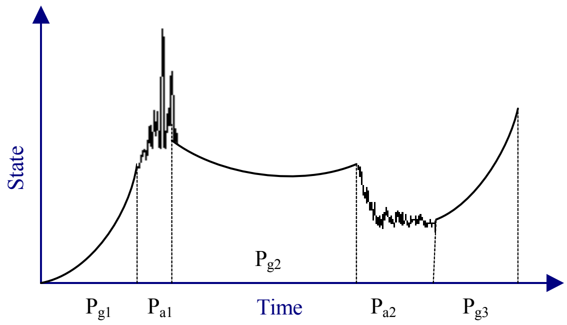

Fig. 3. Gradual changes versus abrupt changes.

In many cases, the continuity and gradualness of a gradual phase make it possible to predict the state after time t by the state before time t. For example, we can predict the air temperature in an hour by how the air temperature changes before now. It is this predictability that enables our approach to achieve its energy-efficiency. Examples of such kind of phenomena include: air temperature, air humidity, earth temperature, soil fertility, soil humidity, body temperature, blood pressure, health of machines or buildings, pH value of lake water, concentration of pollutant, diffusion of contaminants, *etc*.

As for some phenomena, predicting the future state by previous state is very hard, sometimes even impossible. For example, the irregularity of the noise in a workshop makes it difficult to predict its intensity in the future. Our approach is not applicable for monitoring such kind of phenomena.

3.2 Models

Problem Definition: For a sensor node N_i, given the measurement data $\{X_i^0, X_i^1, \ldots, X_i^t\}$ before time instant t, an error bound ε, conclude a predictive model M that minimizes $Num(E_i^{t+a}: |E_i^{t+a} - X_i^{t+a}| \le \varepsilon)$, where $a \ge 1$.

However, at time instant t, $\{X_i^{t+a}, X_i^{t+a+1}, \ldots\}$ are unknown. As a result, these data cannot help us to figure out model M. What we can depend on is the data set $\{X_i^0, X_i^1, \ldots, X_i^t\}$. So what we should do is to derive a proper model M from $\{X_i^0, X_i^1, \ldots, X_i^t\}$ and hope the prediction of M will agree with the actual future measurement data.

The continuity and gradualness of a gradual phase make it can be represented as a unitary function or several unitary functions with time as the independent variables. Based on this, unitary functions with time as the independent variables are adopted as models depicting how the monitored phenomenon changes in a gradual phase. Assume a unitary function $f(x)$ for a phase P_g is derived at time instant t and sent to BS, then BS can use $f(x)$ to estimate the actual state after time instant t.

From above analysis, it can be seen the key problem of our approach is to derive the function $f(x)$ from limited measurement data. This problem can be viewed as a data fitting problem [15]. There are generally three problems to solve: (1) identifying a target function with unknown parameters; (2) identifying a proper data set and (3) determining the unknown parameters of the target function. Problems (2) and (3) will be answered in following sections. Here we answer how to solve problem (1).

What target functions should be adopted is strongly application-dependent. As for different applications, the target functions that should be adopted may be quite different. If the change of the monitored phenomenon follows an obvious function type, then we have an obvious choice. Otherwise, if the function $f(x)$ is continuous and has $(n + 1)$ continuous derivatives on an open interval (a, b), then according to Taylor Theorem [16], for $x \in (a, b)$, $f(x)$ can be represented as the summation of a polynomial of $(x - x_0)$ and a remainder:

$$f(x) = f(x_0) + f'(x_0)(x - x_0) + f''(x_0)\frac{(x - x_0)^2}{2!} + \ldots + f^n(x_0)\frac{(x - x_0)^n}{n!} + R_n(x)$$

where $x_0 \in (a, b)$. Based on this, polynomial functions can be adopted to fit the measurement data if there is not an obvious choice.

Note that time also affects the selection of target functions. For example, it can be seen from Fig. 1 that the blood pressure curve takes on different shapes in different time phases of a day. As a consequence, using only one function to model the blood pressure curve of a whole day is not appropriate. The proper way is that different functions should be taken to model the blood pressure curve in different time phases. By storing multiple target functions for different time phases on nodes, proper functions can be selected according to the time when the model is building.

Although unitary functions are adopted in this paper to represent how the monitored phenomenon changes, this does not mean unitary functions are the only models that can be used. We think adopting what modeling tool is highly application-dependent.

3.3 Energy Consumption and Error

Consider an application that n sensors are deployed to monitor the temperature in an area. The sensors are required to sensing the phenomena every a time interval t_s. Observing that the nodes consume same amount of sensing energy in a time unit under different data gathering approaches, we do not consider the sensing energy in the energy consumption models. And as the energy consumption of computing is relatively small compared to the transmission energy [17], we further simplify the energy model by only considering the transmission energy. In our model, the transmission energy consumed in a time unit is calculated by counting the number of data packets generated by all sensor nodes in a time unit. And we assume that all nodes behave in a same way, so we just use the number of data packets that a node generates and sends to the base station in certain time to evaluate the performance of different approach.

For sake of simplicity, both a measurement datum and a model are regarded as a data packet. No further processing, like aggregation or compression, is done to the data packets when they are transmitted to the base station. A node generates T/t_s packets in time T. Assume a node sends a model to the base station every a time interval t_m in our approach.

In an ideal case, the errors of all estimations of models are within the allowable error bound. For a node, the number of packets sent in time T is T/t_m. If we want to make $T/t_m < T/t_s$, if and only if $t_s < t_m$. In a worst case, a node sends a model to the base station every time t_m, yet no estimation satisfy the error condition. As a result, the node has to send measurement data to the base station. In such a case, a sensor node sends $T/t_m + T/t_s$ packets in time span T.

In a general case, we assume the average probability that estimations of models meet the error requirement is p. The number of packets that a node sends in time T is $T/t_m + T/t_s \times (1 - p)$. Let $T/t_m + T/t_s \times (1 - p) < T/t_s$, we get $p > t_s/t_m$. Value p can be used to judge the effectiveness of the induced model.

As for the error of our approach, we know if the estimation E_i of the model and the actual measurement data X_i satisfy $|E_i - X_i| \leq \varepsilon$, then X_i is not reported to the base station, otherwise X_i is reported to the base station. From this, it can be seen that the maximum error of our approach is the allowable error bound ε.

The allowable error bound ε also has strong connection with the energy consumption. A smaller error bound means heavier traffic and bigger energy consumption, and a larger error bound means lighter traffic and smaller energy consumption. This will be shown by experiments in section 5.

4. IMPLEMENTATION OF APPROACH

In this section, identifying the data set and fitting the data is first discussed, and then the algorithm running on sensor nodes is presented.

4.1 Building the Models

Identifying the data set concerns how to determine the number and location of the data. At a time instant t, what is known to node N_i is the measurement data $\{X_i^0, X_i^1, \ldots, X_i^t\}$ before t, and what we need to do is to derive a function that can predict the measurement data after t. Generally speaking, data that are adjacent in time are more correlated [18]. Based on this, we use the data measured in an interval before time t to fit the target function. As for the length of the interval, on the premise of that the target models can be constructed successfully; the length should be as small as possible. In the experiments presented in section 5, an interval contains only 5 data, yet the result is very satisfactory.

Suppose the chosen data set is (x_i, y_i), $i = 1, 2, \ldots, n$, $x_i \neq x_j$ if $i \neq j$. Let $f(t)$ be the target function and $f(t)$ is expressed as:

$$f(t) = a_1 r_1(t) + a_2 r_2(t) + \ldots + a_m r_m(t) \tag{1}$$

where $\{r_1(t), \ldots, r_m(t)\}$ is a group of predefined functions. $\{a_1, \ldots, a_m\}$ is the coefficients that need to be determined. Least square fitting [15] is adopted by *MADG* to determine $\{a_1, \ldots, a_m\}$. To do this, we need to make expression (2) get the least value.

$$J(a_1, \ldots, a_m) = \sum_{i=1}^{n} [f(x_i) - y_i]^2 \tag{2}$$

According to the necessary conditions for an extremum: $\frac{\partial J}{\partial a_k} = 0$, where $k = 1, 2, \ldots, m$, following group equation is derived:

$$\begin{cases} \sum_{i=1}^{n} r_1(x_i)\left[\sum_{k=1}^{m} a_k r_k(x_i) - y_i\right] = 0 \\ \vdots \qquad \vdots \qquad \vdots \\ \sum_{i=1}^{n} r_m(x_i)\left[\sum_{k=1}^{m} a_k r_k(x_i) - y_i\right] = 0. \end{cases} \tag{3}$$

Group equation can be expressed as:

$$R^T R A = R^T Y \tag{4}$$

where

$$R = \begin{bmatrix} r_1(x_1) & r_2(x_1) & \cdots & r_m(x_1) \\ r_1(x_2) & r_2(x_2) & \cdots & r_m(x_2) \\ \vdots & \vdots & \vdots & \vdots \\ r_1(x_n) & r_2(x_n) & \cdots & r_m(x_n) \end{bmatrix}, \ A = (a_1, \ldots, a_m)^T \text{ and } Y = (y_1, \ldots, y_n).$$

By solving group Eq. (4), $\{a_1, \ldots, a_m\}$ can be derived. If $r_1(t), \ldots, r_m(t)$ are linearly independent, then R^TR is reversible, and Eq. (4) has sole solution. In our approach, this is guaranteed by always using polynomial functions as the target functions.

4.2 Algorithm

In our approach, most of the work is done on sensor nodes. The base station simply uses the models to compute the expected value. A node N_i performs operations shown in Fig. 4 when a data is measured.

```
 1: while (measures a data X) do {
 2:     Add measurement X to DataSet;
 3:     if (X is the first data) then {
 4:         set y = X as the model and send model to BS;
 5:         continue; }
 6:    E = estimate of model;
 7:    if (|E − X| < ε) then continue;
 8:    if (Num(DataSet) < DataNum) then {
 9:        set y = X as the model and send model to BS;
10:        continue; }
11:    f(x) = data fitting result;
12:    bool = false;
13:    for (each data d in DataSet) do {
14:        E = estimate of f(x);
15:        if (|E − d| > ε) then {
16:            bool = true;
17:            set y = X as the model and send model to BS;
18:            break; } }
19:    if bool then continue;
20:    Set f(x) as model and send model to BS; }
```

Fig. 4. Algorithm running on a node.

In the algorithm, data fitting is done only when there are enough data in the data set. The correctness of the built modes has significant impact on the performance. A model that cannot predict the coming measurements accurately can only introduce extra overhead. In the algorithm, lines 13 to 18 are used to guarantee the effectiveness of the model. This can ensure the gain in performance if a correct model is used, and also the performance does not degrade if there is not an accurate model.

5. EXPERIMENTAL RESULTS

The performance of our approach (denoted as Model-Aided) was tested against other two approaches. In one approach (denoted as Simple), all data are sent to the base station. In the other approach (denoted as Cache), the latest measurement data X_l of a node is cached by the node and the base station. A measurement data X_c is sent to the base station only when the absolute value of the difference between X_l and X_c is bigger than error bound ε.

MicaZ motes [19] are used to test the performances of all approaches. Four motes are deployed to monitor the air temperature in the garden outside of our laboratory. We monitored the temperature for 5 days. The monitoring results of four motes are quite similar. Fig. 5 shows the air temperature curve that is drawn from the data collected by a node using approach simple in 40 hours.

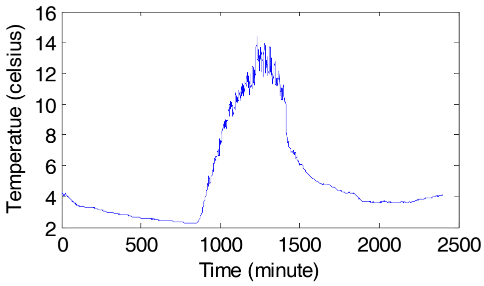

Fig. 5. Air temperature curve.

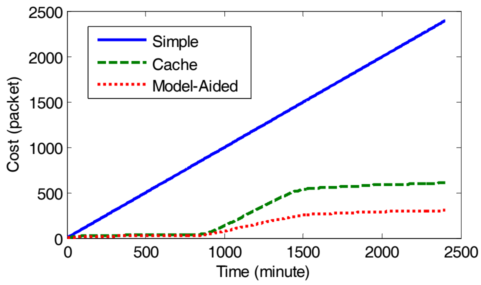

Fig. 6. Packets sent of three approaches.

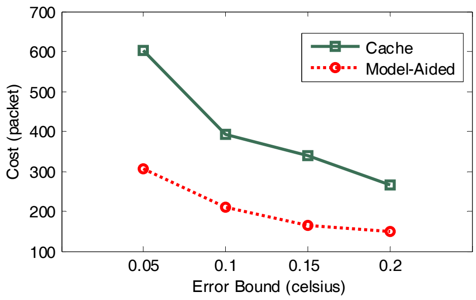

Fig. 7. Error bounds versus cost.

The number of transmitted packets is adopted to evaluate the performances of three approaches. For sake of simplicity, a measurement datum or a model is both regarded as a data packet. A node measures the air temperature every 1 minute. The allowable error bound is 0.05 Celsius. Only linear functions are taken to fit the temperature data. A data-set includes 5 data, *i.e.* data measured in 5 minutes.

Fig. 6 presents the comparative results of three approaches in cost which is evaluated by the number of sent packets. From the figure, it can be seen that even the performance of Cache is much better than Simple. By adopting models, our approach achieves better performance further than Cache.

Fig. 7 reveals the comparative results of two approaches, Cache and Model-Aided, against the error bound. Approach Simple is not compared because the costs of Simple are identical under different error bounds. In both Cache and Model-Aided, the number of sent packets drops as the error bound increases. It can also be observed that Model-Aided outscores Cache under all error bounds.

6. CONCLUSION AND FUTURE WORK

In this paper, temporal rules of the changing processes of natural phenomena are exploited to improve the energy-efficiency of wireless sensor networks. By maintaining replicated models on sensor nodes and the base station, energy can be saved by reducing the data transmitted to the base station. In the future, we will extend our current work in several directions: (i) we will study more complex models to capture the sensory data of more complex applications; (ii) we will carry out more experiments to evaluate the performance of our approach and (iii) we also plan to integrate model-aided approach with spatial rules of natural phenomena and make full use of spatio-temporal rules to heighten the energy-efficiency of wireless sensor network.

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