Implementation and Evaluation of Scalable and Robust Scheme for Data Gathering in Wireless Sensor Networks

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1. Introduction

With the development of low-cost microsensor equipment having the capability of wireless communications, sensor network technology has attracted the attention of many researchers and developers. By deploying a large number of sensors in a monitored region and composing a sensor network of them, one can remotely obtain information on behavior, condition, and position of elements in the region.

In [1], we have proposed a novel and efficient scheme for data gathering in sensor networks where a large number of sensor nodes were deployed. In such networks, nodes are randomly introduced, occasionally die or get removed, and sometimes change their locations. We considered an application that periodically collected sensor information from distributed sensor nodes to a base station. In our scheme, sensor information periodically propagates without any centralized control from the edge of a sensor network to a base station as the propagation forms a concentric circle. By observing the radio signals emitted by sensor nodes in its vicinity, a sensor node independently determines the cycle and the timing at which it emits sensor information in synchrony. For this purpose, we adopted a pulse-coupled oscillator model [2] based on biological mutual synchronization such as that used by flashing fireflies, chirping crickets, and pacemaker cells. Through simulation experiments, we confirmed that our scheme can gather sensor information in a fully-distributed, self-organizing, robust, adaptable, scalable, and energy-efficient manner.

In this paper, to verify the practicality and viability of our proposed scheme, we implement the scheme on an actual wireless sensor network using off-the-shelf sensor nodes, MOTE [3]. Through experiments, we find that our scheme cannot attain the synchronized data gathering due to instable and unidirectional wireless communications. We design and implement threshold-based filters to solve the problem. Experimental results show that our improved scheme can periodically gather sensor information in an energy-efficient manner and it is adaptable to addition and removal of sensor nodes and changes in frequency of data gathering.

2. Scalable and Robust Data Gathering Scheme

The base station emits a beacon signal at a regular interval to make sensor nodes within the range of its radio signal synchronize with each other. Sensor node S_i maintains level l_i, which corresponds to the number of hops from the base station, a timer $\phi_i \in [0, 1]$, and a state $x_i \in [0, 1]$, which is given by a monotonically increasing function $f_i : [0, 1] \to [0, 1]$ of a phase ϕ of the timer. We further define a regulated phase ϕ'_i as,

$$\phi'_i = p(\phi_i, \delta_i) = \begin{cases} \phi_i + \delta_i, & \text{if } \phi_i + \delta_i \leqq 1 \\ \phi_i + \delta_i - 1, & \text{otherwise} \end{cases} \tag{1}$$

From ϕ'_i, we obtain a regulated state x'_i by $f_i(\phi'_i)$. Sensor node S_i emits a message, including the sensor information and its level, when its regulated state x'_i becomes one.

At time t, sensor node S_j receives a message from sensor node S_i in its vicinity. If its level l_i is smaller than S_j's level l_j, S_j is stimulated and its state changes as

$$x_j(t^+) = B(x_j(t) + \epsilon). \tag{2}$$

The regulated state x'_j of stimulated sensor S_j is given as $x'_j = f_j(p(f_j^{-1}(x_j(t^+)), \delta_j))$. When sensor S_j's regulated state x'_j becomes one, it also emits a message in synchrony with sensor S_i. This is regarded as the synchronization.

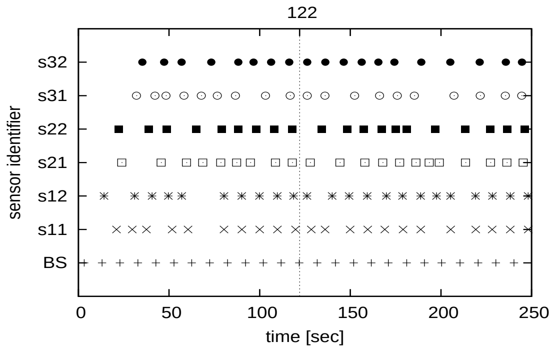

Figure. 1 Timing of message emission with original scheme

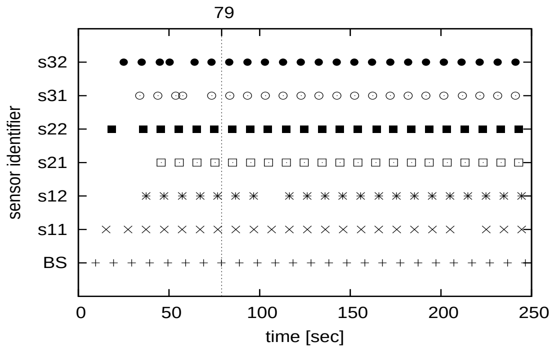

Figure. 2 Timing of message emission with improved scheme

The level that sensor node S_i belongs to is given as the smallest level, say l_j, among messages that sensor node S_i can receive plus one, i.e., $l_i = l_j + 1$. A beacon signal from the base station advertises the level zero.

3. Implementation and Evaluation of Data Gathering Scheme

We first implemented the scheme and conducted experiments. We put six sensor nodes to form a concentric circle around a base station. Dots on lines in Fig. 1 correspond to instants when sensors emit messages. BS stands for a base station. Ten's place of sensor identifier corresponds to a circumference. Around 122 sec, it can be seen that sensors s11 and s12 on the first circumference emited their sensor information at the same timing, which was slightly earlier than a beacon signal by the offset. s21 and s22 (s31 and s32) emited their information earlier than s11 and s12 (s21 and s22), so that their information could be successfully relayed by s11 and s12 (s21 and s22). However, such synchronization was immediately lost due to instable and unidirectional radio communications.

Since sensor nodes emit their signals in synchrony, there occur collisions in radio signals. As a result, a signal arrives at a node slightly behind the appropriate instant. Being stimulated by a delayed signal, a sensor node wrongly adjusts its timer and the synchronization is lost. In addition, objects and structures around a sensor network reflect radio signals. As a result, a signal from an unexpectedly distant node occasionally arrives at a sensor node. It mis-identifies its level and thus cannot attain the synchronization. To solve these problems, we introduce three filtering mechanisms. On reception of a signal, a sensor node first compares the signal strength to a threshold and ignores weak signals. Then, it considers the number of signal receptions from the same sensor node. If it exceeds a threshold, the signal is considered stable. Finally, if the reception is right after the sensor node emits its information, it ignores the signal to avoid being stimulated by delayed signals. As Fig. 2 shows, with these modifications, sensor nodes could successfully attain the synchronization and sensor information propagated from the most distant nodes to the base station at the appropriate timing and frequency.

4. Conclusion

In this paper, we first evaluated our synchronization-based data gathering scheme experimentally in a sensor network consisting of commercial, off-the-shelf wireless sensor units. Since we verified that the scheme could not establish the synchronization-based data gathering when the wireless communications were unstable, we proposed filtering mechanisms and found that our thus-improved scheme could periodically gather sensor information from sensor nodes and adapt to changes in sensor networks.

Acknowledgement

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[3] "MOTE." available at `URL: <http://www.xbow.com/Products/Wireless_Sensor_Networks.htm>`.

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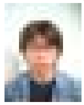

Synchronization-based data gathering scheme

- A scalable, robust, and energy-efficient scheme for periodic data gathering in sensor networks
- Sensor information periodically propagates from the edge of a sensor network to a base station
  - Each sensor node has a timer
  - Each sensor node needs to turn on its transceiver component only at regular intervals
- Synchronization is accomplished without any centralized control by adopting pulse-coupled oscillators model
  - Scalable because of no centralized control
  - Adaptive to the addition, removal, and movement of sensor nodes without any manual operations

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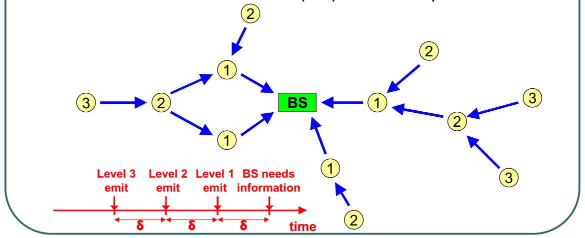
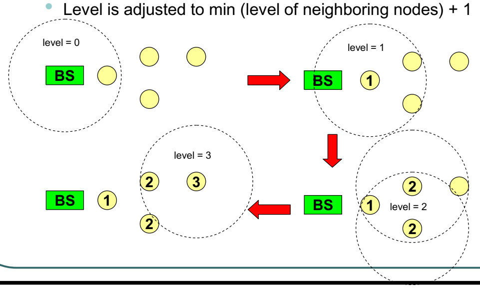
Data gathering scheme

- Sensor nodes emit their sensor information based on their own timers, but in synchrony with others of the same number of hops (called level)
- Sensor information propagates from the edge of sensor network to a base station (BS) – multi-hop



Level adaptation

- Each sensor node determines its level through reception of messages of other sensor nodes or BS
  - Message : sensor ID, sensor information, level
  - Level is adjusted to min (level of neighboring nodes) + 1

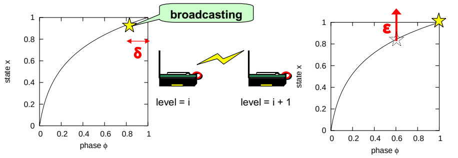


Synchronization scheme

- Each sensor node has state x and phase ϕ

  $x = f_i(\phi_i) = \frac{1}{b}\ln[1+(e^b-1)\phi_i]$ (0≦x ≦1, 0≦ϕ≦1)
- Sensor information is emitted at $\phi = 1 - \delta$
- A message of a lower level node raises state x by ε

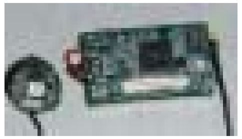
  When x is raised to 1, synchronization is accomplished



- BS emits beacon signals at regular interval

Implementation on MOTE

- We implemented our scheme in sensor networks composed of wireless sensor units :MOTE



- We proposed several improvements to solve problems on using our scheme in real environments
  - Delayed radio signals
  - Unstable radio signals

Problems in real environments and their solutions

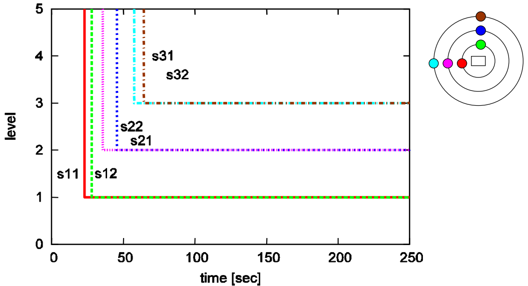
- Delayed radio signals
  - Synchronization is lost when state of the sensor nodes is raised by delayed signals

    Solution
  - Ignore radio signals discriminated to be delayed
- Unstable radio signals
  - Radio signals of further sensor nodes accidentally reach to a sensor node, level is wrongly identified
  - Sensor node can't attain synchronization and becomes isolated

    Solution
  - Ignore radio signals whose reception strength are too weak
  - Ignore radio signals which infrequently arrive (less than twice in three timer cycles)

Result - level identification

- All sensor nodes identify their levels appropriately



Result - synchronization

- The global synchronization was maintained, once it was obtained at 79 sec