國立交通大學

網路工程研究所

碩 士 論 文

以適應性水閘資料匯集系統用於長鏈狀無線感測網路之研究

Adaptive Lock Gate Designation Scheme for Data Aggregation in Long-Thin Wireless Sensor Networks

研 究 生：莊哲熙

指導教授：曾煜棋　教授

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摘　　　要

因為物理環境的限制，近幾年來無線感測網路中，長鏈狀網路晉升為許多實際部屬的拓樸結構。一般來說，長鏈狀拓樸是由多條長鏈狀分之所組成，每條分之由多個感測點相連而成，而每個感測點都只有一個父節點。在長鏈狀拓樸下，即使資料匯集可以降低無線感測網路中多餘的封包競爭，資料匯集還是會受到最大封包資料量的限制。這篇論文提出長鏈分之中應該放置都個資料匯集點，稱作水閘，負責匯集上游一般感測點的資料。這篇論文針對長鏈狀無線感測網路提出一個適應性水閘指定方法，該方法在無線感測網路回報效率以及資料收集壅塞程度中取得平衡，並且減輕無線感測網路中的漏斗效應。該方法更動態的調整水閘的位置及數量以適應網路中隨時間變化的流量。實作結果顯示出適應性水閘指定方法確實能改善長鏈狀網路的效能。

關鍵字：資料匯集，長鏈狀網路，普適計算，無線感測網路。

Adaptive Lock Gate Designation Scheme for Data Aggregation in Long-Thin Wireless Sensor Networks

Student: Che-Hsi Chuang   Advisor: Prof. Yu-Chee Tseng

Department of Computer Science
National Chiao-Tung University

ABSTRACT

Constrained by the physical environments, the *long-thin* (LT) topology has recently been promoted for many practical deployments of wireless sensor networks (WSNs). In general, an LT topology is composed of long branches of sensor nodes, where each sensor node has only one potential parent node toward the sink. Although data aggregation may alleviate excessive packet contention, constraints imposed by the maximum payload size of a packet severely limit the amount of sensor readings that may be aggregated along a long branch of sensor nodes. This paper argues that multiple aggregation nodes, termed *lock gates*, need to be designated along a branch to aggregate sensor readings sent from their respective upstream sensor nodes (up to the other upstream lock gate(s) and/or the end of the branch). The paper further describes an adaptive lock gate designation scheme for LT WSNs, which balances the responsiveness and the congestion of data collection, and mitigates the funneling effect. The scheme also dynamically adapts the designation of lock gates to accommodate the time-varying sensor reading generation rates of different sensor nodes. Experimental results demonstrate the effectiveness of the scheme.

Keywords: Data aggregation, long-thin network, pervasive computing, wireless sensor network.

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莊 哲 熙 謹識於

國立交通大學網路工程研究所碩士班

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Contents

Abstract i

誌謝 iii

Contents iv

List of Figures v

1 Introduction 1

2 Related Works 6

3 The Proposed ALT Scheme 8

4 Experimental Results 15

5 Conclusions 21

Bibliography 22

List of Figures

1.1 An example of LT WSNs **2**

1.2 An LT WSN and its lock gates **3**

3.1 Examples of moving next lock gates: (a) $g1$ moves $g3$ down- stream due to $T_1 < T_{\min}$, (b) $g1$ moves $g2$ to the branch node b due to $T_1 < T_{\min}$, (c) $g1$ moves $g2$ upstream due to $T_1 > T_{\max}$, and (d) $g1$ moves $g3$ to node s due to $T_1 > T_{\max}$ .. **11**

3.2 Counterexamples of moving next lock gates **12**

4.1 The prototype of our LT WSN experiments **15**

4.2 Three LT topologies in our experiments **15**

4.3 The change of the positions of lock gates when all sensor nodes have the same sensor reading generation rate **19**

4.3 The change of the positions of lock gates when sensor nodes have different sensor reading generation rates **20**

Chapter 1

Introduction

A *wireless sensor network* (WSN) consists of a sheer number of sensor nodes, where each sensor node is a wireless device that reports sensor readings of its surroundings to a sink node via multi-hop ad hoc communications. Such networks facilitate pervasive monitoring of the physical environments to enable applications such as habitat monitoring, smart home, and surveillance [5, 12, 13].

In recent research, the *long-thin* (LT) topology has been promoted for many practical applications of WSNs where the sensor deployment is subject to environmental constraints [11]. For instance, a surveillance system of moving cars along streets, a monitoring system of carbon dioxide inside tunnels, and a monitoring system of water quality within sewer lines are typical examples. Fig. 1.1(a) depicts the physical deployment of sensor nodes along streets, and Fig. 1.1(b) depicts its corresponding LT topology. In general, an LT topology is formed by a bunch of long 'branches' and each branch may be composed of tens or hundreds of nodes. For each sensor node along a branch, there exists only one potential parent node toward the sink. Branches are connected at *branch nodes*, and Fig. 1.1(b) shows an example where a branch node is denoted with double circles.

Let $\{s_1, s_2, \cdots, s_n\}$ denote the node IDs of an LT WSN, where n is the number of sensor nodes. By viewing an LT topology as a shortest-path tree

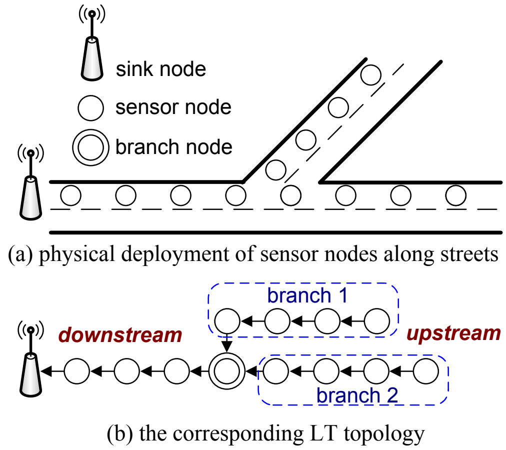


Figure 1.1: An example of LT WSNs.

rooted at the sink, let d_i be the depth of node s_i from the sink. Assuming that each sensor node in the LT WSN transmits one sensor reading to the sink without aggregating data, the network will incur $\sum_{i=1}^{n} d_i$ transmissions to collect all of the sensor readings. For instance, the LT WSN of Fig. 1.1 incurs 62 transmissions if no data aggregation is taken. Worse, an LT WSN may exhibit the funneling effect where the hop-by-hop traffic over a long branch results in an increase in transit traffic intensity, collision, congestion, packet loss, and energy drain as packets move closer toward the sink [2].

Now consider the following aggregation scheme. The leaf nodes start transmitting their sensor readings first. Each intermediate node *waits* to aggregate its own sensor reading with the (aggregated) sensor reading(s) sent from its child(ren), and then forwards the aggregated packet toward the sink. Such scheme may result in only n packet transmissions in the network, assuming that successively aggregated sensor readings could be loaded into one big packet. For instance, the LT WSN of Fig. 1.1 may incur only 12 transmissions using such aggregation scheme. Fewer transmissions benefit WSNs by conserving energy and reducing contention.

Although such aggregation maximally reduces the number of transmissions in an LT WSN, constraints imposed by the maximum payload size $L_{\max}$

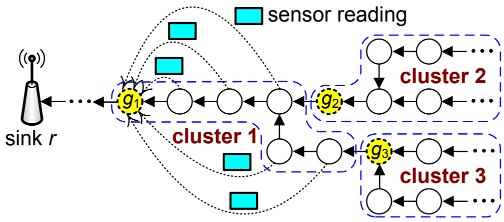


Figure 1.2: An LT WSN and its lock gates.

of a packet and the compression ratio δ ($0 < \delta \leq 1$) make such scheme impractical for an LT topology where a node may only aggregate up to $\lfloor \frac{L_{\max}}{\delta} \rfloor$ bytes of sensor readings, while the total data size of sensor readings generated by sensor nodes of a (long) branch in an LT topology may well exceed this bound.

To mitigate the funneling effect and to comply with the maximum payload size, the paper suggests that along a branch, multiple aggregation nodes, termed *lock gates*[1] in the paper, need to be designated, where each lock gate aggregates its own sensor reading with all of the sensor readings sent from its upstream sensor nodes (up to immediate, upstream lock gate(s) or the end of the branch) subject to the $\lfloor \frac{L_{\max}}{\delta} \rfloor$ bound. For instance, as shown in Fig. 1.2, assuming $L_{\max}$ is 3 bytes, δ is 0.5, and the size of sensor readings is 1 byte, we designate one lock gate every six sensor nodes so that lock gate g_1 aggregates its own sensor reading with those from its five upstream nodes into one aggregated packet[2]. Similarly, this can be done by lock gates g_2 and g_3. Such an aggregated packet (of maximum payload size $L_{\max}$) is said to be completely *filled up* with sensor readings and thus can be forwarded to the sink without being aggregated with any other sensor readings along the way.

Another benefit of the above lock gate design is that it actually reduces

[1] We were inspired by the lock gates used in canals to withstand the water pressure arising from the level difference between adjacent pounds. In the context of LT WSNs, (irregular) network traffic from sensor readings corresponds to water pressure, which should be regulated to mitigate funneling effect, for instance.

[2] Here we assume that there is no 'protocol overhead' (or packet header/trailer) so that the size of a packet is exactly the same as the size of its payload.

contention among traffic by spatially separating areas where packets are transmitted. In the above example, since lock gates g_2 and g_3 will *hold* their transmissions until enough sensor readings from the corresponding upstream nodes have been collected, the members of the cluster led by lock gate g_1 can transmit their sensor readings to g_1 with little or even no interference coming from clusters of lock gates g_2 and g_3.

However, since sensor nodes may generate sensor readings at different *rates*, each lock gate may wait for a different amount of time to completely fill up an aggregated packet of size $L_{\max}$. Let λ_j denote the sensor reading generation rate (bytes/second) of sensor node s_j. Let $C(g_i)$ denote the *cluster* of nodes containing lock gate g_i and its upstream sensor nodes, up to immediate, upstream lock gate(s) or the end of the branch. Assuming that each λ_j is a constant and the WSN operates at a steady state, the following equation indicates the amount of time T_i taken by lock gate g_i to completely fill up an aggregated packet of size $L_{\max}$.

$$\left(T_i \times \sum_{s_j \in C(g_i)} \lambda_j\right) \times \delta = L_{\max}. \tag{1.1}$$

When T_i is large, the sink is expected to wait for a longer time to receive an aggregated packet from lock gate g_i, which increases the response time of monitoring. Large T_i may imply either the size of $C(g_i)$ is small or the total sensor reading generation rate of the sensor nodes in $C(g_i)$ is low, or both. In contrast, small T_i may imply either the size of $C(g_i)$ is large or the total sensor reading generation rate of the sensor nodes in $c(g_i)$ is high, or both. This may result in too many packet transmissions and thus congest the network.

This paper proposes an *adaptive lock gate designation scheme*, termed *ALT*, to facilitate effective data aggregation in LT WSNs. Given a pair of time thresholds, ($T_{\min}$, $T_{\max}$), specified by the application of an LT WSN to balance the response time of collecting sensor readings and the congestion caused by transmitted packets, ALT designates lock gates in an LT WSN such that for each lock gate g_i, $T_{\min} \leq T_i \leq T_{\max}$. Specifically, when sensor reading generation rate λ_i varies over time, ALT dynamically adjusts the positions of lock gates (and thus the definitions of clusters) to balance response time and congestion. To the best of our knowledge, this is the first effort that addresses efficient data aggregation in LT WSNs.

The remainder of this paper is organized as follows. The next section describes related work. Section 3 describes our ALT scheme. Section 4 reports our prototyping efforts and experimental results. Section 5 concludes the paper.

Chapter 2

Related Work

The subject of data aggregation in WSNs has been extensively studied. However, most research efforts used either a tree-based or a cluster-based architecture to aggregate data in WSNs, and none of them considered the LT topology.

Tree-based aggregation schemes use the shortest path routing tree, and focus on how to choose a good routing metric based on data attributes to facilitate data aggregation. For instance, the work of [6, 8] proposed a data-centric approach to select an appropriate path to reduce energy consumption. In addition, the work of [1] built an aggregation tree according to the energy consumption of sensor nodes. Each node predicts the energy consumption of its potential parents and selects the one that can be left with the most energy as its parent. In contrast, in LT WSNs, there exists at most one route from a sensor node to the sink (*i.e.*, each sensor node has at most one potential parent node toward the sink) so that existing solutions may not be directly applied.

In comparison, cluster-based aggregation schemes group sensor nodes into clusters and perform aggregation within each cluster. For instance, in LEACH [4] and PEGASIS [10], sensor nodes relay their sensor readings to the corresponding cluster heads, which are assumed to be able to communicate directly with the sink. However, this assumption is not valid in LT

WSNs. In addition, HEED [14] groups sensor nodes such that sensor nodes within a cluster are single-hop away from the cluster head. However, in an LT WSN, sensor nodes within a cluster are located along a long branch which are multi-hop away from their cluster head. SCT [15] proposed a ring-sector division clustering scheme, where sensor nodes in the same section are assembled into one cluster. Clearly, this approach cannot be used for LT WSNs. Reference [3] considered aggregating data without maintaining any structure. It proposed a MAC protocol and studied the impact of randomized wait time to improve aggregation efficiency. However, this scheme may increase packet delays in LT WSNs.

Chapter 3

The Proposed ALT Scheme

The LT topology is first proposed in [11]. We model an LT WSN as graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V} = \{r\} \cup \mathcal{S}$ contains the sink r and the set of sensor nodes $\mathcal{S}$, and $\mathcal{E}$ contains all of the communication links. The topology of $\mathcal{G}$ is represented as a tree rooted at sink r. Each sensor node $s_j \in \mathcal{S}$ has a sensor reading generation rate of λ_j, which may vary over time during the network operation. A sensor node is called a *branch node* if it has more than one child in $\mathcal{G}$. Fig. 1.2 depicts an example of LT WSNs, where three clusters are identified and nodes g_1, g_2, and g_3 are designated as lock gates.

Given an LT WSN, ALT first randomly groups sensor nodes into several non-overlapping clusters covering the entire network, and designates their corresponding lock gates. Note that the sensor node closest to the sink is always designated as a lock gate. On generating one sensor reading, each regular sensor node will send the reading to its corresponding lock gate. Each lock gate g_i then collects the sensor readings from the sensor nodes within its cluster $C(g_i)$. After collecting enough sensor readings that can be aggregated to fill up one packet of maximum payload size $L_{\max}$, lock gate g_i sends the packet toward the sink. To reduce the latency of waiting to aggregate enough sensor readings to fill up one packet of maximum payload size $L_{\max}$, lock gate g_i may dynamically adjust its cluster according to the duration T_i that it took to generate the previous aggregated packet (referring to Eq. (1.1)). When T_i is below a given lower-bound threshold $T_{\min}$, the total sensor reading generation rate within this cluster (*i.e.*, $\sum_{s_j \in C(g_i)} \lambda_j$) becomes too high, and aggregated packets will be sent to the sink more often. In this case, lock gate g_i 'shrinks' its cluster by excluding certain sensor nodes to lower the total sensor reading generation rate. In contrast, when T_i is above a given upper-bound threshold $T_{\max}$, the total sensor reading generation rate within this cluster becomes too low, and the monitoring quality degrades. In this case, lock gate g_i 'expands' its cluster by including more sensor nodes to lower the latency of generating aggregated packets. Note that within each cluster $C(g_i)$, the sensor readings sent from each sensor $s_j \in C(g_i)$ may be relayed to lock gate g_i in a pipeline manner subject to the contention of wireless transmissions. Thus, right before lock gate g_i sends out each (completely filled) aggregated packet toward the sink, the percentage of sensor readings received from sensor s_j within this packet is approximately equal to $\frac{\lambda_j}{\sum_{s_k \in C(g_i)} \lambda_k}$. In other words, ALT ensures that the amount of reported sensor readings from each sensor node is fairly proportional to the sensor reading generation rate of that sensor node.

Before describing ALT in details, we first define the terms used in the remainder of the paper. A lock gate g_k is called a *next lock gate* of lock gate g_i if g_k is an immediate upstream lock gate of g_i. In this case, g_i is the *previous lock gate* of g_k. For example, in Fig. 1.2, g_2 is a next lock gate of g_1 while g_1 is a previous lock gate of g_2. Note that each lock gate may have multiple next lock gates but at most one previous lock gate. In addition, a lock gate is called a *leaf lock gate* if it has no next lock gate; otherwise, it is a *non-leaf lock gate*.

From an initial lock gate designation, lock gates execute ALT *asynchronously*, while coordinating with previous and next lock gates. Each lock gate g_i measures its current T_i value, 'moves' one of its next lock gates (if necessary) downstream or upstream by one-hop, and recalculates its T_i value. This process is repeated until lock gate g_i settles at $T_{\min} \le T_i \le T_{\max}$. Specifically, for each non-leaf lock gate g_i, two cases are considered:

Case of $T_i < T_{\min}$: In this case, lock gate g_i shrinks its cluster by first querying each of its next lock gates g_k for its T_k value. If lock gate g_k is also in the state of adjusting its own next lock gates, lock gate g_k will reply to lock gate g_i that itself is *busy*; otherwise, lock gate g_k will reply to lock gate g_i for its T_k value. If lock gate g_i finds that all of its next lock gates are busy, it will wait for a Δ_t time and try again. Otherwise, lock gate g_i sends a *pull* message to the next lock gate g_k whose parent node, say, s_j on graph $\mathcal{G}$ is not a branch node *and* whose T_k value is the largest. On receiving such a pull message, lock gate g_k designates sensor node s_j to become a new lock gate and clears itself as a lock gate. In this case, the old cluster $c(g_k)$ disappears and a new cluster $c(s_j)$ appears. For convenience, we use the term 'move' to represent such an operation. However, in the case that lock gate g_i cannot find such a next lock gate (which means that the parent nodes of all of its next lock gates on $\mathcal{G}$ are branch nodes), the next lock gate g_k that has the maximum T_k value is asked to move one-hop downstream. These operations are repeated until lock gate g_i computes that $T_i \geq T_{\min}$.

Fig. 3.1(a) gives an example, where g_1 wants to adjust one of its next lock gates g_2 and g_3. Since the parent node of lock gate g_2 is a branch node, lock gate g_3 will be asked to move downstream. When all of the parent nodes of all of its next lock gates are branch nodes, as shown in Fig. 3.1(b), assuming $T_2 > T_3$, ALT will ask lock gate g_2 to move to node b.

To avoid excluding too many sensor nodes when shrinking a cluster, which may make its T_i value increase drastically, ALT avoids moving a next lock gate whose parent node on $\mathcal{G}$ is a branch node as much as possible. Fig. 3.2(a) shows a counterexample, where we assume $T_2 > T_3$. If g_1 simply moves its next lock gate whose T_i value is the largest, g_2 will be asked to move downstream, as shown in Fig. 3.2(b). In this case, the size of cluster $c(g_1)$ will drastically decrease from 7 to 3. Moreover, the size of cluster $c(g_2)$ will drastically increase from 8 to 12. In fact, ALT will move g_3 downstream

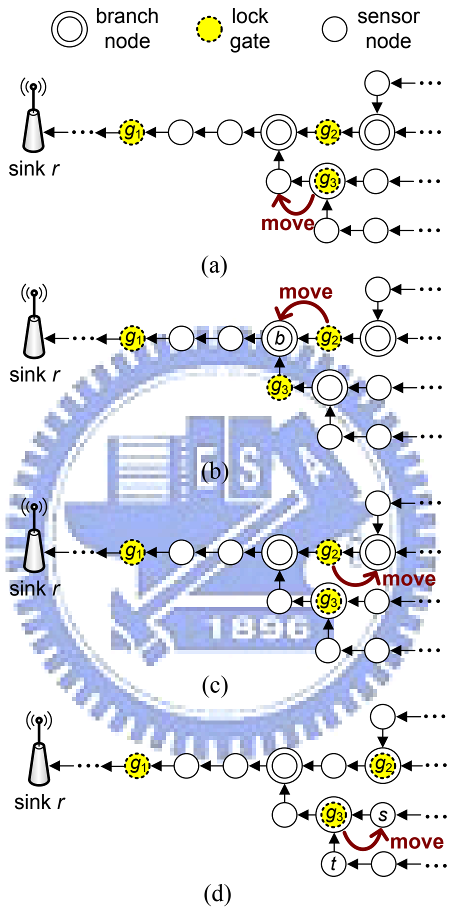


Figure 3.1: Examples of moving next lock gates: (a) g_1 moves g_3 downstream due to $T_1 < T_{\min}$, (b) g_1 moves g_2 to the branch node b due to $T_1 < T_{\min}$, (c) g_1 moves g_2 upstream due to $T_1 > T_{\max}$, and (d) g_1 moves g_3 to node s due to $T_1 > T_{\max}$.

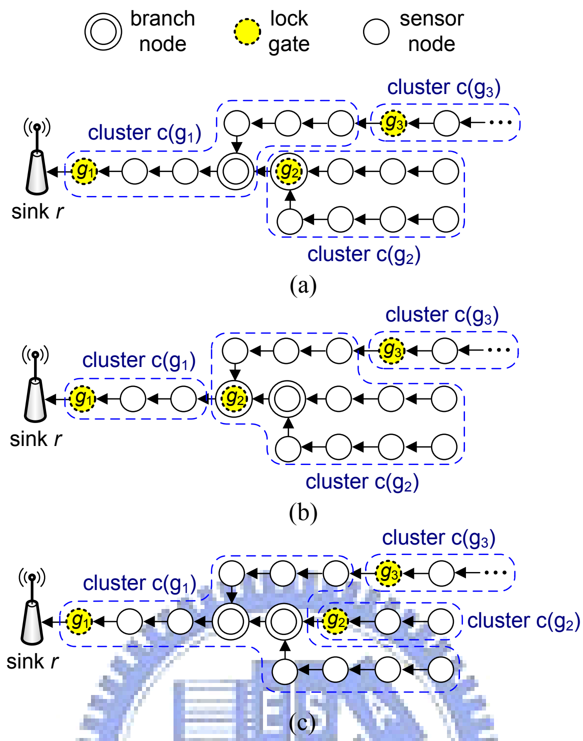


Figure 3.2: Counterexamples of moving next lock gates.

instead.

Case of $T_i > T_{\max}$: In this case, lock gate g_i expands its cluster by first querying each of its next lock gate g_k for its T_k value. If lock gate g_k is also in the state of adjusting its own next lock gates, it will reply to lock gate g_i that itself is busy; otherwise, it will reply to lock gate g_i for its T_k value. If lock gate g_i concludes that all of its next lock gates are busy, it will wait for a Δ_t time and try again. Otherwise, lock gate g_i sends a *push* message to ask the next lock gate g_k that is not a branch node *and* has the minimum T_k value to move one-hop upstream. In the case that lock gate g_i cannot find such a next lock gate (which means that all of its next lock gates are branch nodes), the next lock gate g_k that has the minimum value of T_k will be asked to move upstream. These operations are repeated until lock gate g_i computes that $T_i \leq T_{\max}$.

Fig. 3.1(c) gives an example, where g_1 wants to adjust one of its next lock gates g_2 and g_3. Since lock gate g_2 is not a branch node, it will be moved upstream. When all of the next lock gates are branch nodes, as shown in Fig. 3.1(d), assuming that $T_3 < T_2$, ALT will ask lock gate g_3 to move to node s. Note that in the latter case, g_3, t, and some of t's subsequent nodes will be merged into the cluster $c(g_1)$.

Similar to shrinking a cluster, to avoid including too many sensor nodes when expanding a cluster, which may make its T_i value decrease drastically, ALT avoids moving a next lock gate that is a branch node as much as possible. Fig. 3.2(a) shows a counterexample, where we assume $T_2 < T_3$. If g_1 simply moves its next lock gate whose T_i value is the smallest, g_2 will be asked to move upstream, as shown in Fig. 3.2(c). In this case, the size of cluster $c(g_1)$ will drastically increase from 7 to 12. Moreover, the size of cluster $c(g_2)$ will drastically decrease from 8 to 3. In fact, ALT will move g_3 upstream instead.

For each leaf lock gate g_i, it will be moved according to the push or pull request from its previous lock gate. Moreover, two special cases must be considered. First, if g_i is asked to move upstream but itself is already a leaf node in $\mathcal{G}$, then g_i will simply clear itself as a lock gate and become a regular sensor node. In this case, the total number of lock gates in the network decreases by one. Second, if g_i is asked to move downstream but finds that $T_i < T_{\min}$, it will do as requested and select one leaf node, say, s_j in its cluster and designate s_j as a new lock gate. In this case, the total number of lock gates in the network increases by one.

To prevent lock gates from oscillating or moving back and forth between two adjacent nodes, each lock gate g_i should maintain a short list recording its past positions on $\mathcal{G}$. If lock gate g_i finds that it has moved between two adjacent nodes (termed *oscillating nodes)* more than β times and its previous lock gate still asks it to move to one of the oscillating nodes, it enters the *oscillating state*. In this case, lock gate g_i will notify its previous lock gate to stop asking it to move in that direction. Lock gate g_i will exit the oscillating state if its previous lock gate asks it to move to one non-oscillating node or a pre-set oscillating timer expires.

When each sensor node has a fixed sensor reading generation rate, the lock gates designated by ALT will eventually stabilize and converge (from an initial random designation) due to the following two factors. First, a lock gate can only move its next lock gates but cannot move its previous lock gate. In this case, clusters stabilize *in sequence* from the downstream direction to the upstream direction. Second, ALT employs the oscillation avoidance technique described in the previous paragraph.

We now analyze and compare the latency of sending packets from each sensor node s_j to sink r with and without applying ALT. Assume that s_j is located within cluster $C(g_i)$. Let $D_{j,i}$ and $D_{i,r}$ be the latency of a packet from sensor node s_j to lock gate g_i and from lock gate g_i to sink r, respectively. When no lock gate is used, the latency of a packet from sensor node s_j to sink r is $D^{\mathrm{NL}}_{j,r} = D_{j,i} + D_{i,r}$. In contrast, by using ALT, since lock gate g_i will send its aggregated packet to sink r after T_i, we have

$$D^{\mathrm{L}}_{j,r} \leq D_{j,i} + T_i + D_{i,r} = D^{\mathrm{NL}}_{j,r} + T_i. \tag{3.1}$$

By combining Eqs. (1.1) and (3.1), ALT can only increase the packet latency as follows:

$$D^{\mathrm{L}}_{j,r} - D^{\mathrm{NL}}_{j,r} \leq \frac{L_{\max}}{\delta \times \sum_{s_k \in C(g_i)} \lambda_k}.$$

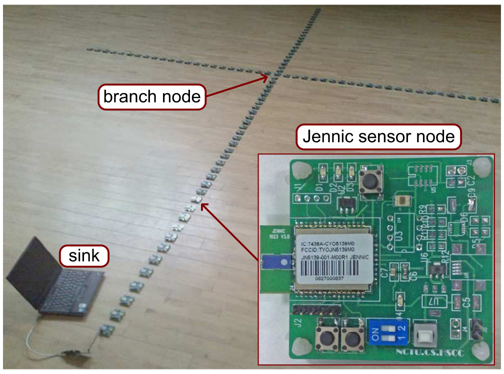


Figure 4.1: The prototype of our LT WSN experiments.

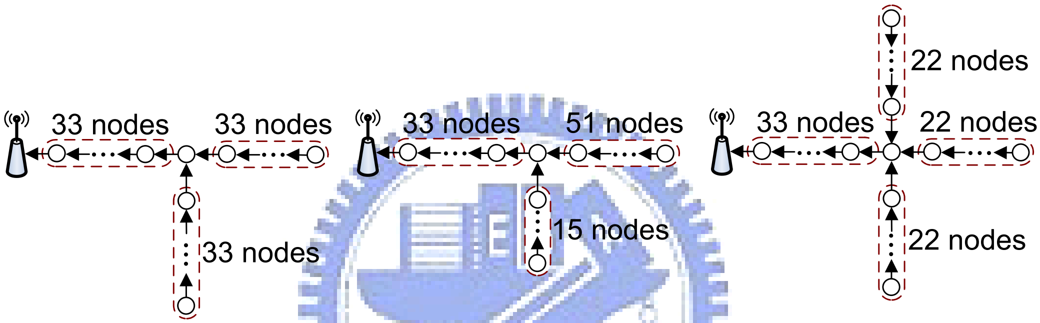


Figure 4.2: Three LT topologies in our experiments.

Chapter 4

Experimental Results

In this section, we describe our prototyping efforts and experimental results. We deploy one hundred sensor nodes and one sink node to collect data from the environment, as shown in Fig. 4.1. Each sensor node contains a Jennic JN5139 chip [7], which is a low power, wireless micro-controller supporting the IEEE 802.15.4 protocol. Each sensor node has a communication distance of approximately 30 centimeters (cm). We place two adjacent nodes with a distance of 15 cm to make the network connected. Three LT topologies are deployed in our experiments. The *balanced* topology (Fig. 4.2(a)) has two branches, each with 33 nodes. The *unbalanced* topology (Fig. 4.2(b)) has two branches, one containing 51 nodes while the other containing 15 nodes. The *cross* topology (Fig. 4.2(c)) has three branches, each with 22 nodes. We compare ALT against the *brute force* (BF) and the *fixed lock gate selection* (FLS) schemes using these three network topologies. BF does not apply any aggregation, where each sensor node simply relays the sensor readings from its upstream nodes to the sink. In FLS, each branch node is designated as a lock gate and we do not adjust the designation of lock gates during the experiments.

The packet size of a sensor reading is 15 bytes, which contains a header of 12 bytes (according to the IEEE 802.15.4 standard [9]) and a payload of 3 bytes. Each sensor node reports its sensor reading every Δ_s seconds, where Δ_s is randomly selected from $[(1-\alpha)\times 10, (1+\alpha)\times 10]$ and it may be changed every 30 seconds. Note that when $\alpha = 0$, the sensor reading generation rate (*i.e.*, λ_i) is 0.3 bytes/second. We adopt a simple aggregation scheme by removing the packet headers of all of the received sensor readings and then concatenating their payloads into one single packet. In this way, we have $\delta = 1$. In our experiment, we set $L_{\max}$ as 118 bytes, which is the maximum payload size of a packet defined in the IEEE 802.15.4 standard. The total experiment time is 10 minutes. In the experiments of running ALT, the measurement of messages sent by sensor nodes includes all of the control messages (*e.g.*, query, reply, push, and pull) used to adjust the designation of lock gates. Other parameters used in the experiments are set as follows: $\beta = 3$, $\Delta_t = 2$ seconds, $T_{\min} = 24$ seconds, and $T_{\max} = 26$ seconds.

Table 4.1: Comparison on the total amount of messages (in bytes) sent by sensor nodes in different network topologies.

α value	scheme	balanced	unbalanced	cross
$\alpha = 0$	ALT	498,530	581,550	468,982
	FLS	668,962	785,707	572,769
	BF	928,926	1,022,398	864,898
$\alpha = 0.3$	ALT	525,009	606,598	502,592
	FLS	680,349	801,486	596,287
	BF	943,384	1,096,538	871,232

Table 4.1 shows the total amount of messages sent by sensor nodes in different network topologies. BF suffers from the highest amount of messages because it does not apply any aggregation. By dynamically adjusting the positions of lock gates according to the network condition, ALT enjoys a lower amount of messages compared with FLS. It can be shown that when $\alpha = 0$, ALT saves 18.1% to 26.0% and 43.1% to 46.3% of message transmission compared with FLS and BF, respectively. When $\alpha = 0.3$, ALT saves 15.7% to 24.3% and 42.3% to 44.7% of message transmission compared with FLS and BF, respectively. These results show the effectiveness of ALT. Note that the three schemes all suffer from the highest amount of messages under the unbalanced topology, because this topology has the longest branch (with 51 nodes). In addition, when $\alpha = 0.3$, the amount of messages increases because sensor nodes generate more sensor readings. In this case, since the network is not stable, ALT needs to generate more control messages to adjust the designation of lock gates.

Table 4.2 shows the total number of packets sent by sensor nodes in different network topologies. When sensor nodes transmit more packets, the network could be more seriously congested. BF makes the sensor nodes transmit the most number of packets, since it does not aggregate any sensor reading. ALT enjoys the smallest number of packets among all three schemes because it adaptively clusters sensor nodes and aggregates their packets accordingly. We observe that when $\alpha = 0$, ALT saves 59.1% to 72.3% and

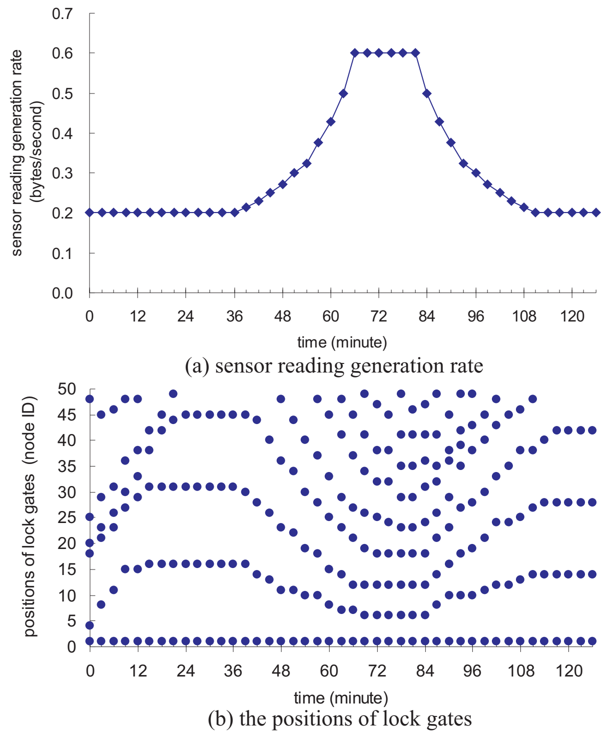
Table 4.2: Comparison on the total number of packets sent by sensor nodes under different network topologies.

α value	scheme	balanced	unbalanced	cross
$\alpha = 0$	ALT	35,878	35,517	32,225
	FLS	99,915	128,396	78,767
	BF	238,899	267,690	217,392
$\alpha = 0.3$	ALT	33,865	35,788	33,033
	FLS	103,750	128,563	81,621
	BF	240,855	282,288	218,911

85.0% to 86.7% of packets compared with FLS and BF, respectively. When $\alpha = 0.3$, ALT saves 59.5% to 72.2% and 84.9% to 87.3% of packets compared with FLS and BF, respectively. These results demonstrate that ALT significantly reduces the number of packets sent by sensor nodes, which can greatly alleviate the network congestion.

To demonstrate the adaptability of ALT to varying sensor reading generation rates, we deploy a sink (of ID 0) and a line of 50 sensor nodes (of IDs 1 to 50), where the node with ID 1 is the most downstream sensor node. The duration of the experiment is 126 minutes and we measure the (changing) number of lock gates and their designation (or positions) over time. All of the sensor nodes have the same sensor reading generation rate (λ), which changes every 3 minutes as shown in Fig. 4.3(a). For instance, starting at 0.2 byte/second, λ remains at the same rate until the 36th minute, increases to 0.6 bytes/second at the 66th minute, remains at the same rate until the 81st minute, and then decreases. Fig. 4.3(b) depicts the changing designation of lock gates, as dots, over time. For instance, at 0th minute, there are 6 lock gates randomly designated at nodes of IDs 1, 4, 18, 20, 25, and 48. Before the 36th minute, λ is not changed and thus the positions of lock gates stabilize at nodes of IDs 1, 16, 31, and 45 at the 24th minute. As λ increases, the size of the clusters decreases and the number of lock gates increases accordingly. Between the 66th to the 81st minutes, λ remains stable and thus the positions of lock gates are only slightly adjusted. For instance, at the

72nd minute, 8 lock gates are designated at nodes of IDs 1, 6, 12, 18, 25, 32, 38, and 47. After the 81st minute, as λ decreases, the number of lock gates also decreases and the size of clusters increases. After the 117th minute, the position of lock gates remains stable because λ becomes stable. Since all of the sensor nodes have the same λ value, we also observe that the distance between any two adjacent lock gates is quite similar at most time instances. Such a phenomenon is more visible when the number of lock gates is smaller. These observations demonstrate that ALT can efficiently adjust the size of each cluster (and designate the lock gate accordingly) based on the traffic sent from the sensor nodes in that cluster.

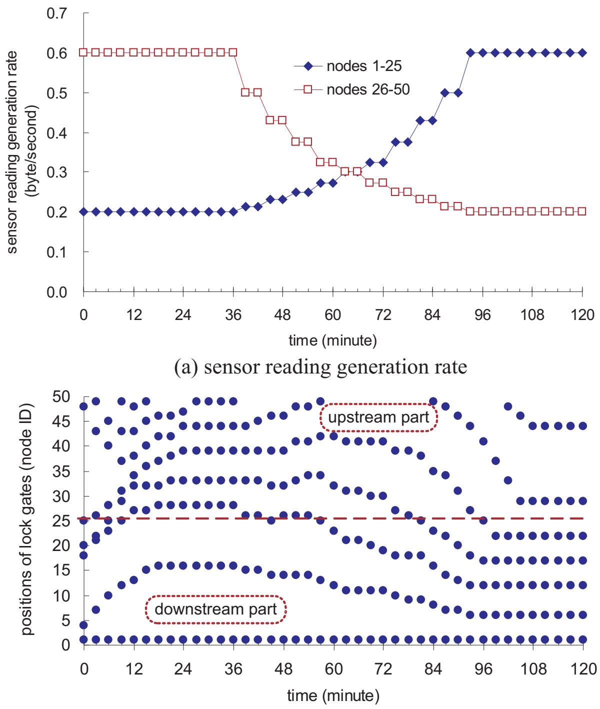


(a) sensor reading generation rate

(b) the positions of lock gates

Figure 4.3: The change of the positions of lock gates when all sensor nodes have the same sensor reading generation rate.

Using the same network topology in the previous experiment, we also demonstrate the adaptability of ALT when sensor nodes have different sensor reading generation rates (λ). Specifically, the λ value of sensor nodes of IDs 1 to 25 increases while that of sensor nodes of IDs 26 to 50 decreases over time, as shown in Fig. 4.4(a). For convenience, we use the terms 'downstream part' and 'upstream part' to represent the sensor nodes of IDs 1 to 25 and of IDs 26 to 50, respectively. The duration of the experiment is 120 minutes. Beginning with the same random lock gate designation as the previous experiment, Fig. 4.4(b) shows the positions of lock gates over time. We observe that before the 60th minute, most lock gates are located at the upstream part because sensor nodes in the upstream part have a higher sensor reading generation rate. Thus, ALT shrinks the sizes of clusters in the upstream part and thus designates more lock gates. After the two sensor reading generation rates cross around the 66th minute, the behavior reverses. Most lock gates move to the downstream part due to the fact that sensor nodes in the downstream part have a higher sensor reading generation rate.



(a) sensor reading generation rate

(b) the positions of lock gates

Figure 4.4: The change of the positions of lock gates when sensor nodes have different sensor reading generation rates.

Chapter 5

Conclusions

Many realistic WSN applications dictate the deployment of an LT topology which demands new data aggregation schemes. The paper described the ALT lock gate designation scheme which (1) designates multiple lock gates within an LT WSN to regulate data aggregation and (2) adapts the designation of lock gates dynamically in response to changing sensor reading generation rates of sensor nodes. ALT balances the responsiveness and the congestion of data collecting, and mitigates the funneling effect by regulating (aggregated) data that could be transmitted downstream and spatially separating areas where packets are transmitted. Using the Jennic JN5139 wireless micro-controllers, we evaluated the performance of ALT via several experiments of prototyped LT WSNs. Experimental results demonstrated the merits of ALT. Research is in progress to further analyze and quantify the impact of designating multiple lock gates on MAC layer contention and packet loss.

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