Master Thesis

A Research on Communication Protocol for Information Gathering over Wireless Sensor Networks

無線センサネットワークにおける情報収集に適した
通信プロトコルに関する研究

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Abstract

This thesis proposes and implements the specific communication protocol for information gathering in wireless sensor networks (WSNs). Several designs of routing systems to collect information from the network of wireless sensors have been practically used in real-world applications, however, not satisfied the requirements in terms of unreliable information delivery and high data transmission overhead. In this work, the technique inspired by Directed Diffusion has been applied to the network construction. The specific route-creation message is flooded throughout the network and the spanning communication tree is established concurrently with the message propagation. This research enhances the link selection process by using the Handshaking. In addition, the Packet Link Layer is introduced to control Data Retransmission on top of MAC Layer. This is to strengthen the fundamental communication links by retransmitting identical messages in case of transmission failure. Finally, the Dynamic Route Alteration (DRA), a mechanism to dynamically change the routing path, is proposed so that the network can move to better structure of communication links during the operation phase. The DRA is executed in case that the message delivery is out of control for the Packet Link Layer. Subsequently, the DRA is triggered in order to alter the parent node of the wireless sensor in trouble. The thesis presents evaluation results of proposed mechanism performance on TOSSIM, a simulator of TinyOS, and reveals fundamental tradeoffs on energy, reliability and throughput. The performance evaluation showed that the combination of proposed mechanisms outperformed current approaches in term of higher reliability of information gathering.

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Chapter 1

Introduction

1.1 Background

Technological trends currently enable the creation of an inexpensive, small and intelligent sensor, a so-called wireless sensor. The wireless sensors are a new type of smart sensor device which is enabled the capabilities to communicate each other via wireless radio-wave channel. Also, it can process simple operations as a computer which enables the smart sensor to operate as a light-weight processing unit. These abilities facilitate new categories of application of sensor including surveillance, traffic monitoring, environmental monitoring and objects tracking which were hard or more complicated to be implemented by old-fashion sensor technology. Practically, those applications consist of hundreds or even thousands of wireless sensors deployed to the operating area which obstructs manually setting of specific parameters. These enforce applications to function in a self-configurable manner.

Since size and cost of devices are the main considerations in wireless sensor networks, it implies that resources available to individual sensor are severely limited. Small devices can contain only limited amount of energy. In addition, since battery charging or replacement may be hindered by the nature of applications, energy awareness is a significant issue in WSNs.

According to typical applications of WSNs which involves in directly interacting with environment, those can be seen that one of common but indispensable operation is information gathering. As can be seen in monitoring systems which the base station receives information submitted from wireless sensors in the network or even other applications for specific purposes, wireless sensors need the function to send their reports to the centralizing units.

Although many studies on communication protocols have recently been proposed, some of them have designed under different assumptions such as communication protocols for other ad-hoc network which are plentiful of resources such as memory, computational power or energy, some of them are too general which possibly cause a waste of energy in case of using in particular purpose such as the information gathering. Hence, in order to archive the best performance, a specific communication protocol may need to be uniquely designed.

This research aims to develop a special communication protocol for the information gathering. Since one of the most energy-expensive operations in WSNs is data transmission, the communication significantly influences the length of life time of applications. The information gathering system or module are in charge of both preparing infrastructures to gather data and managing the information collecting process in a manner that consumes the energy as less as possible and provides the best performance of reliable information delivery.

1.2 Objective and Scope of Thesis

The main objective of this research is to achieve higher reliability of the information gathering an energy-saving manner. Since energy is the main constraint in WSNs, the reliability and energy efficiency are valued as the primary attributes and this thesis leaves other typically important attributes including latency, throughput and bandwidth utilization to be secondary.

In this thesis, the author assumes that the information gathering module is used in the surveillance system to control the report delivery from wireless sensors to the base station. The research is done under the hypotheses that wireless sensors are densely deployed to the operating area and no dynamic characteristic change of communication links during the operation. At the end of the study, the author expects to develop a ready-to-use set of components for executing in TinyOS.

1.3 Outline of Thesis

The reminder of this thesis is organized as follows. The next section presents the prototype of the surveillance system and current works related to the information gathering system. Section 3 describes the design of mechanisms proposed in order to improve the performance of information gathering. Section 4 shows the performance evaluation of proposed approaches and the analysis and discussion of results. Finally, section 5 concludes the research.

Chapter 2

Surveillance System using Wireless Sensor Networks and Current Works Related to Information Gathering

This chapter describes a prototype of surveillance system over wireless sensor networks. As the main objective of this thesis, the information gathering system is developed to serves the information delivery task in the surveillance system. To better understand more about the surveillance system in WSNs, this chapter contains its system architecture, design and working cycle. Subsequently, the current works which have been practically used as a module in charge of information gathering are introduced.

The organization of this chapter is as follows. Firstly, section 2.1 describes key characteristics of wireless sensor network and TinyOS, a de-facto standard operating system for sensor networks. The requirements of the surveillance system then are explained in section 2.2. Next, section 2.3 and 2.4 briefly present of the system structure and the system design of the surveillance, respectively. Section 2.5 concludes the contributions of this thesis in the surveillance system and a fundamental concept of information gathering by many-to-one communication scheme is introduced in section 2.6. Finally, this chapter ends with current widely used routing systems for information gathering in section2.7.

2.1. TinyOS

The surveillance system operates over wireless sensor networks which have many unique properties. This subsection describes those characteristics which enforces the design and structure of applications to be particularly done in specific manner different from other types of ad-hoc systems.

The major difference between wireless sensor networks and other types of ad-hoc networks are concluded as follows.

First, the number of sensor nodes in a sensor network is usually larger than in ad-hoc networks. Thousands or more of wireless sensors are possibly used in one application while the number of nodes working in one application for other types of ad-hoc system tends to be much smaller.

Second, sensor nodes may not have global identification in WSNs. Sensor queries in sensor networks are often data-centric, rather than node-centric. Queries are not directed toward a specific node but to where the requested data exists.

Third, Energy consumption is the biggest constraint. Power recharging is often impractical and wireless communication contributes a major part to energy consumption. Therefore, reducing communication is the key to energy conservation.

Fourth, sensor nodes are prone of failures. Sensor nodes may fail due to lack of power, physical damage. Therefore, robustness and flexibility are important design issues in sensor networks.

Fifth, sensor nodes are intended to work in any environment, including some environments where deployment can not perform carefully. Moreover, due to sensor node failures or environmental changes, self-configuring and topology maintenance mechanisms are required to guarantee efficient transmission of the information.

Finally, in contrast to end-to-end communications in ad hoc networks, the dominating communication paradigm is many-to-one data flows. All these reasons, sensor networks provide an environment that encourages reconsidering of existing communication protocols.

Because of several special characteristics as mentioned above, wireless sensors need a specific operating system. Because of the typically different requirements of applications and the resource constraints, operating systems for wireless sensor network nodes are typically less complex than general-purpose operating systems. For example, sensor network applications are usually interactive with physical environment, which is not interactive in the same way as applications for PCs. So, the operating system does not need to include support for user interfaces. Moreover, the resource constraints in terms of memory make mechanisms such as virtual memory either unnecessary or impossible to implement.

TinyOS is the first operating system specifically designed for wireless sensor networks. Unlike most other operating systems, TinyOS is based on an event-driven programming model instead of multithreading. TinyOS systems are composed into *event handlers* and *tasks* with run to completion-semantics. When an external event occurs, such as an incoming data packet or a sensor reading, TinyOS calls the appropriate event handler to handle the event. Event handlers can post tasks that are scheduled by the TinyOS kernel some time later. Both the TinyOS system and programs written for TinyOS are written in a special programming language called NesC which is a dialect of the C programming language.

TinyOS programs are built out of software components, some of which represent hardware abstractions. For instances, there is a *led* component to switch small led lamps on or off. Components are connected to each other using interfaces. TinyOS provides interfaces and components for common abstractions such as packet communication, routing, sensing and storage.

TinyOS is completely non-blocking; it has a single stack. Therefore, all I/O operations that last longer than a few hundred microseconds are asynchronous. These operations are split-phase and have a callback when the tasks are done. TinyOS uses NesC's features to link these callbacks, called events, statically to enable the compiler to better optimize across call boundaries. While being non-blocking enables TinyOS to maintain high concurrency with a single stack, it forces programmers to write complex logic by stitching together many small event handlers. To support larger computations, TinyOS provides tasks, which are similar to a deferred procedure call. A TinyOS component can post a task, which the OS will schedule to run later. Tasks are non-preemptive and run in FIFO order. TinyOS code is statically linked with program code, and compiled into a small binary.

2.2. System Requirements

The typical requirements of surveillance system are concluded as follows.

- **Durability:** In practice, a surveillance application may have to operate for long time with a large number of sensor nodes. This condition precludes manual one by one battery charging. Power limitation motivates a study of energy conservation. Hence, we need an energy-aware design to extend the lifetime of sensor nodes.
- **Robustness:** Hundreds or thousands of sensor nodes simultaneously work in WSNs. A portion of nodes possibly stops working from battery depletion or unpredictable accidents. Moreover, the unreliable communication in WSNs possibly causes high packet loss rate and further drop the quality of information delivery. Therefore, the system must be designed beforehand to tolerate to these kind of problems and can continue its execution without jitter.
- **Effectiveness:** The precision of tracking result is in general the key metric to determine the effectiveness of a surveillance system. This research is to study a trade-off between energy consumption and tracking performance. There are many factors influent affect both of power consumption and performance of service and this research intends to present consequence of each parameter varying in order to find the most proper configuration.

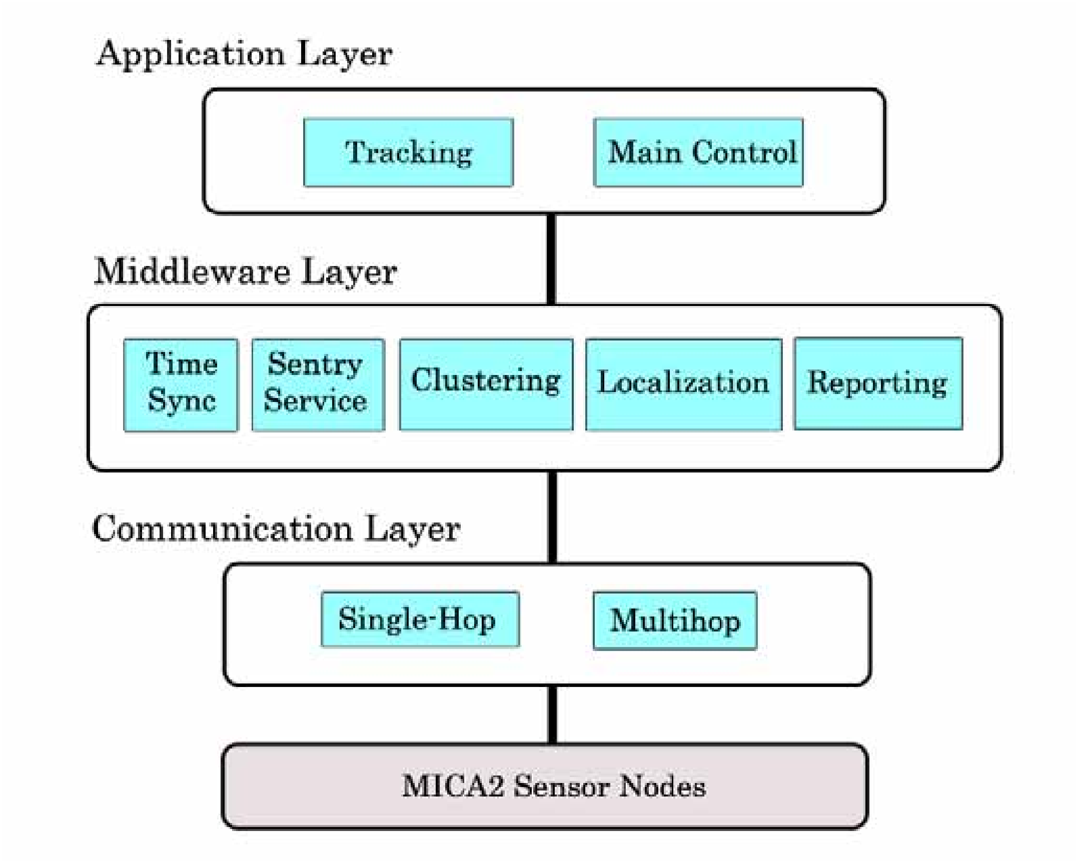


Figure 2.1: System Architecture of surveillance system over WSNs.

2.3. System Structure

The surveillance system is organized into a layered architecture as shown in figure 2.1. Components can be divided into 3 levels by a duty in control.

In the communication layer, TinyOS provides a *single-hop level communication* component. For an application needs *multi-hop communication* like the surveillance system in this thesis, users must develop a module to serve the multi-hop communication service by themselves. The multi-hop data delivery will be used when wireless sensors detect a target and want to submit a report to the base station. This part of the system is the main interest of this thesis and a concept of many-to-one communication scheme will be used on the implementation.

In the middleware layer, *time synchronization* module is responsible for synchronizing the local clocks of the motes with the clock of the base station. The *localization* module is responsible for ensuring the position of each mote. In a real world application, there are many approaches for sensor nodes to locate their own position. For example, the walking GPS solution which the information of position is assign to sensor nodes at the deployment [14. This method operates well for non-mobile sensor networks. *Sentry service* is responsible for collaborative detection of events. It conserves energy by assigning a subset of sensor nodes defined to be sentries which monitor events. The remaining nodes are allowed to sleep until events are detected. When sentries detect an event, they awaken sleeping sensor nodes and the *clustering* module will set sensor nodes into groups in order to perform collaborative tracking. These two modules are the two key services for energy-efficient object tracking.

In the application layer, there is a *tracking* component to control all operations involving in tracking including producing various attributes of events such as moving route and speed based upon gathered information.

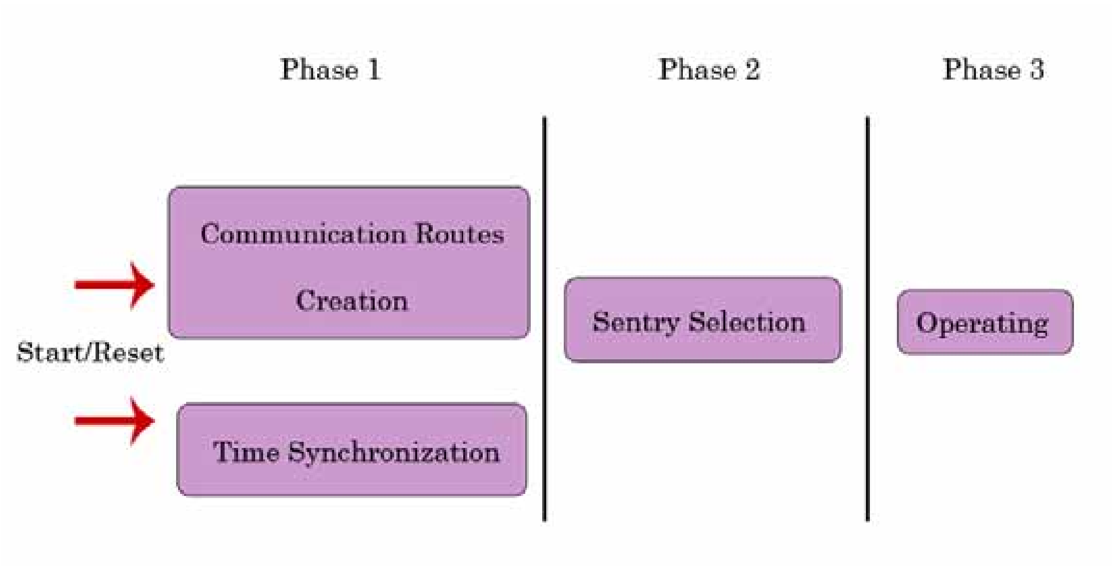


Figure 2.2: Working Cycle of Surveillance System

2.4. System Design

The surveillance system starts up through an initialization process. Fundamental operations including communication routes creation, time synchronization and sentry selection are done during the initialization. As shown in figure 2.2, the initialization process is composed of 2 smaller stages so that wireless sensors are able to avoid the interference of communication between different operations. If all operations perform simultaneously, the communication channel possibly congest with traffic leading to high packet loss rate. The transition between phases is driven by time.

2.4.1 Initialization Phase

Communication routes creation and time synchronization are first carried out. Performing both of these tasks concurrently in one flooding operation reduces data transmission. As mentioned before, data transmission is a relatively expensive operation.

In addition, TinyOS has a relatively high overhead in standard communication packet. The packet header is 7 bytes (MAC header + CRC) and the preamble overhead is 20 bytes in MICA2. For a default payload size of 29 bytes, the overhead of one packet is 48 percents. This restriction motivates users to utilize space in a payload as much as possible to conserve energy consumption.

- **Communication Routes Creation**

In the surveillance system, the communication routes are for sensor nodes to submit reports to the base station after detect incoming objects. Therefore, it has limited destination of any packet which is the base station, and is the one-way communication from sensors to the base station. This unique requirement encourages considering a specific routing protocol to directly fit the requirements and remove redundant waste of data transmission caused by other unneeded feathers.

For above mentioned requirements, data delivery model of this system is in an event-driven manner rather than a query-driven manner which the base station broadcasts a demand of information or the time-driven which sensor nodes periodically send data in every certain interval. Therefore, importing existing communication protocols is eliminated since current routing protocols have mostly been designed in time-driven and query-driven manners.

Due to the requirement of the surveillance system, the concept of many-to-one communication scheme, which will be described more detail in section 2.6, is considerable a suitable candidate to provide communication paths for sensor node to communicate with the base station. The communication spanning tree is proactively constructed to cover the network of sensors rooted at the base station.

- **Time Synchronization**

There are several researches working on how to synchronize the clock of the nodes. GPS-based schemes provide synchronization with a precision of approximately

200ns. However, using GPS devices is not practically used because of its expensive cost both in term of price and power consumption. There are a number of other methods to coordinate the clock without need of a special hardware component. The widely used time synchronization mechanisms developed for WSN domain are the Reference Broadcast Synchronization (RBS) [2] and the Flooding Time Synchronization Protocol (FTSP) [3]. In the RBS, a reference message is broadcasted. The receivers record their local time when receiving the reference broadcast and exchange the recorded times with each other. The main advantage of RBS is that it eliminates transmitter-side act but the message overhead in maintaining the neighborhood information is high [2, 3].

The algorithm used in FTSP applies a MAC-layer time-stamping with several error-reducing techniques to achieve high precision of time synchronization. FTSP introduces a mechanism to estimate the clock drift from the frequency difference of the crystals used in sensor nodes. For the experiment in [3], the clock drift can cause about 40μs time difference between two nodes in 30 minutes. The author of FTSP claimed in [7] that the average error of FTSP outperformed RBS algorithms.

In this surveillance system, a lightweight version of FTSP with cutting periodic re-synchronization feature off is considerable more appropriate in order to reduce energy consumption. To optimize the use of payload, a synchronization beacon is broadcasted by the base station to both synchronize the clock of sensors and construct the communication spanning tree at the same flooding operation.

2.4.2 Sentry Selection

Activities of sensors which consume a large amount of energy consist of data transmission and sensing operation. When a system is in an idle state, sensors must keep periodically sensing. In this process, if all sensors simultaneously track an existence of target, it is a waste of energy since more than one sensors check an existence of target at the same position at the same moment. For each any point in operating area, being tracked by multiple sensors is meaningless. Therefore, assigning only a portion of sensor nodes to act as a sentry, watching over the operating area and awakening up others, is a more reasonable approach.

In this phase, each mote locally makes a decision whether it is going to work as a sentry. A word *sentry* represents a sensor node which monitors an object. The sentries are in charge of their own region and awaken the other sleeping nodes only when intruding targets are detected. By the sentry service, only a portion of wireless sensors are active which prolong the lifetime of non-sentry nodes.

The fundamental idea of assigning sentries is that, when a sensor decides to become a sentry, it simply broadcasts its request. However, there are 3 practical issues need to be concerned including:

- *Advertisement Collision*: This incident occurs when wireless sensors in the same neighborhood broadcast its request to become a sentry at the same time. Sensor nodes can prevent from the collision by using a random back-off delay to transmit a *sentry declare* message so that the request to be a sentry tends not to be broadcasted at the same moment. Any node, which receives the *sentry declare* message, updates its neighborhood table and cancels any pending *sentry declare* messages. After that, it then re-evaluates its decision to become a sentry based on the updated neighborhood information and repeats the sentry declaration process again, if necessary.
- *Energy Balancing*: By setting the back-off delay inversely proportional to the amount of remain energy, a node with more energy has a greater possibility to become a sentry and thereby balancing the energy dissipation uniformly across the network. The back-off delay of a sensor node is also inversely proportional to the number of neighbors that are not covered by a sentry. Thus, wireless sensors in a region at which sensing coverage is still insufficient are favored for being selected as sentries. The key feature of this sentry selection algorithm is that it provides a self-configuring technique for choosing sentries purely based on local information. However, the lack of global knowledge may result in a non-optimal number of sentries.
- *Sensing Coverage*: Surveillance requires the sensing coverage of the physical points in the deployed area. As mentioned, a sensing range is much smaller than a radio communication range, thus the *sentry declare* messages must be broadcasted by lower transmission power setting to ensure sensing coverage. The power setting is chosen in such a way that the communication range equals to a sensing range.

Sentry service plays important role on energy conservation. The described technique seems to exchange information in a saving manner during the selection process. Moreover, there is no requirement of position information which reduces the complication.

2.4.3 Operation Phase

In operation phase, the system has communication routes ready to delivery any report to the base station, synchronized clock and sentries to monitor any incoming target. Wireless sensors then stand by for events to trigger them up. While operating, sensor nodes switch between stand-by and tracking mode.

- **Stand-by Mode**

Sentries periodically check whether there is any object moving around them while non-sentry nodes make a transition to the sleep state to conserve power. If a target is detected, the sentry transmits the awaken beacon to wake non-sentries in its charge up.

In a real wireless sensor platform such as MICA2 [4], there are levels of sleep mode, 6 levels for MICA2. The lower sleeping mode is set, the less power consumption is. However, setting the sleep mode to the lowest level shuts down most of hardware components except for the memory, a timer, and the interrupt handler, therefore, components in responsible for data transmission is turn off and wireless sensors can not receive the signal to wake up from sentries. Energy consumption at the lowest level of working cycle reduces to less than 1 percent of the active mode but users to need to consider of how non-sentry nodes receive command during sleeping. There are many researches to deal with this issue such as in [5], the authors of this work proposed the idea to develop a trigger system to signal a transition from sleep mode to active mode by energy in radio communication signal. A special hardware component is connected to one of the interrupt inputs of the processor which is always running even the deepest level of sleep mode.

- **Tracking Mode**

The sensors change to the tracking mode when any event is detected by sentries. A simple way to track events is by allowing each node to sense the target, write done its location and other relevant information down the report and individually submits to the base station. The advantage of this approach is that complex processing such as, a precise position of target, will be calculated at the base station. However, because there is no collaboration between neighbors and all sensor nodes in the same neighborhood are in fact tracking the same target, reports with the same detail of event are redundantly transmitted which make traffic unreasonably higher. The wasteful consumption of energy can be reduced by aggregating multiple reports and sending a digest.

This is a task in the application layer; the redundant data may be combined along the route to the base station or a system has a group of cooperatively working nodes and the group leader is in charge of aggregating data.

- **Static Clustering :**

As approximately introduced, the concept of in-network data aggregation effectively reduces the amount of data transmission. With the computational capability of wireless sensor, the in-network information processing has become possible. To do the data aggregation, the system needs to form up groups of collaboratively working nodes, a so-called nodes clustering. Node clustering can be categorized as *static* and *dynamic* types. For the *static clustering*, members of each group do not dynamically change during operating. By the current design of the surveillance system, sensor nodes are divided into groups each controlled by the sentry. So, the network has already arranged as groups having sentries working as cluster leaders and non-sentry nodes as members. When the sentry detects a target, it can act as a collector to locally gather sensing results from other nodes in the same group and produces a digested report. The report digestion can be the location estimation or simply packing many reports to compressed format to enhance utilization of payload in a report packet.

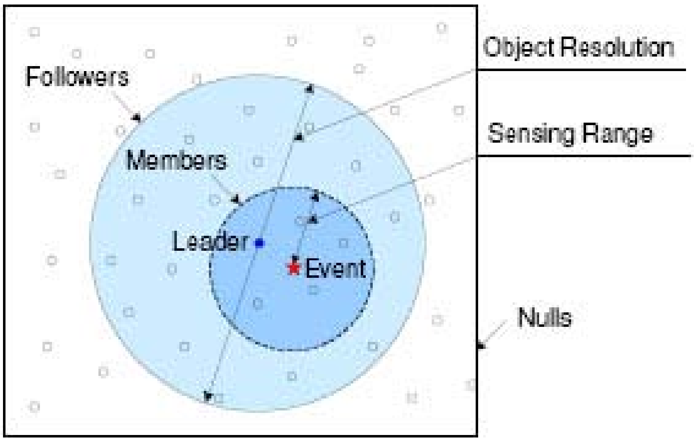


Figure 2.3: Dynamic Clustering

- **Dynamic Clustering:**

In *dynamic clustering*, members of each group are not static. Wireless sensors in the same group are sensor nodes which are detecting the same event. Therefore, the members change depended on the position of the event. The main contribution of the dynamic clustering is to establish a one-one mapping between groups and physical events.

Gu., L. et al described in [6] one choice of the algorithm to implement the dynamic clustering. In this work, the sensor nodes create an event identity to the event and the members use the identity to indicate the source of data. Each group has a leader to perform the data aggregation and be responsible for reporting to the base station.

The potential group leaders are a member which is satisfied 2 following conditions; being a current member of the group and being a sentry. The reason that the group leader must be a sentry is to decrease the contention. And in each group, there is definitely at least one sentry theoretically so the system derives benefit from this fact. If there is only one leader candidate, it implicitly works as a leader. Otherwise, the leader election is carried out. The *implicit leader election* scheme allows candidates to individually start executing the leader tasks such as data aggregation, whenever they detect the target [6]. As a result, multiple potential leaders are executing tasks in a group. If the candidate that first reaches the end of the leader tasks sends out a result report, other neighboring potential leaders simply accept the result and become inactive in their current task which prevents them from sending the same redundant results to the base station.

Apart from regular members, there is a set of nodes called *follower* which represents a non-member node locating within the communication range of the leader as shown in figure 2.3. A sensor node becomes a *follower* when it is wakened up and gets report message from the leader. At this stage, the node maintains the group information, such as target identity, and prepare for incoming target which perhaps enter into its sensing range. Because radio communication range is much longer than sensing range, the area of member nodes is always surrounded by the area of follower nodes as shown in figure 2.3.

- **Location Estimation and Message Digestion:**

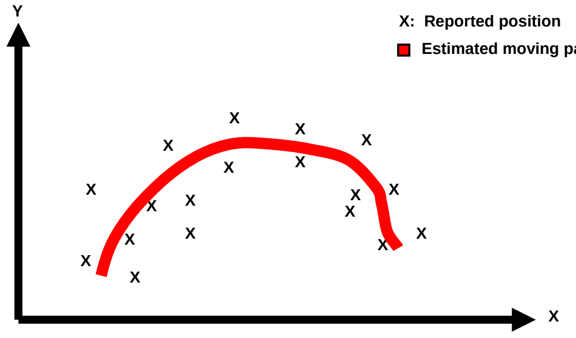


Figure 2.4: Estimation of moving path of the object

The Report from each sensor nodes contains time and the position of the event and these information will be further used to computer other attributes of the tracking event. The calculation can be taken place at the plentiful of computational resource node like the base station. After receives reports from cluster leaders, the base station estimates the location of events and maintains their moving histories. If there are multiple targets and the events are not differentiated at a group level, the base station must classify and group reports with the data source together by using history of moving paths.

The information of each event at the base station is a set of coordinates between time and position where the event has passed nearby. So there must be the process to estimate a moving path and create a smoother track as in figure 2.4.

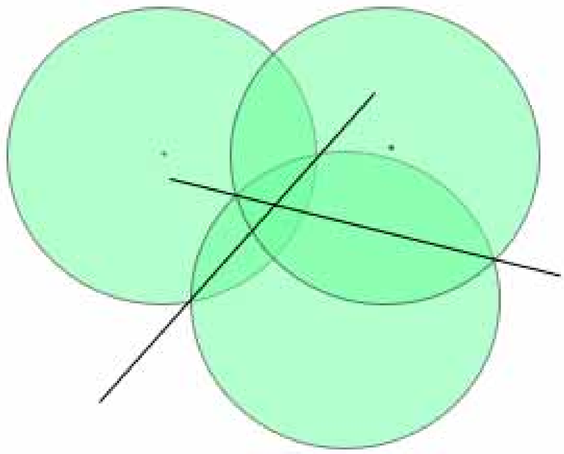


Figure 2.5: Triangulation Method

The last important issue is the message digestion. To utilize a payload in a packet, a group of sensor nodes is established and the leader packs all sensed information into the same packet and lets the packet deliver multiple reports to the base station at the same time. Message digestion reduces the energy consumption from data transmission by decreasing overall overhead caused from delivering the same amount of raw data. The message digest can be enhanced to the higher level of data reduction. In previous digestion paradigm, many reports, which each consist of time and a coordinate of locations, are simply packed into one packet. Compressing these data by estimating the location of the event at the leader can even reduce more the number of packets needed to carry reports. For instance, suppose that there are 5 slots in 1 packet and each slot can contain 1 report. When a group leader simultaneously receives 10 reports from members, it needs two packets to contain and no space remains. On the other hand, if the group leader calculates the position of the event by the same approximation method used at the base station, 10 instances of reports can be digested to 1 which requires only 1 slot space in a packet. Therefore, 1 packet can carry 5 results compressed from 50 reports, which, if no in-network message digestion, need 10 packets to delivery to the base station. Therefore, the in-network location estimation plays an important role to reduce traffic.

Triangulation method is one of widely used algorithm to approximate the position of the object. As depicted in figure 2.5, centers of the circles represent the position of sensor nodes and a radius equal to the maximum sensing range; 2 straight lines are drawn through the intersections of 2 arbitrary pairs of circles and the intersection of these 2 linear lines is the approximated position of the target.

2.5 Conclusion of Working Scope

Section 2.2, 2.3 and 2.4 described the prototype of surveillance system and the observation of related works on each part of the system. However, this thesis focuses on the communication route creation stage.

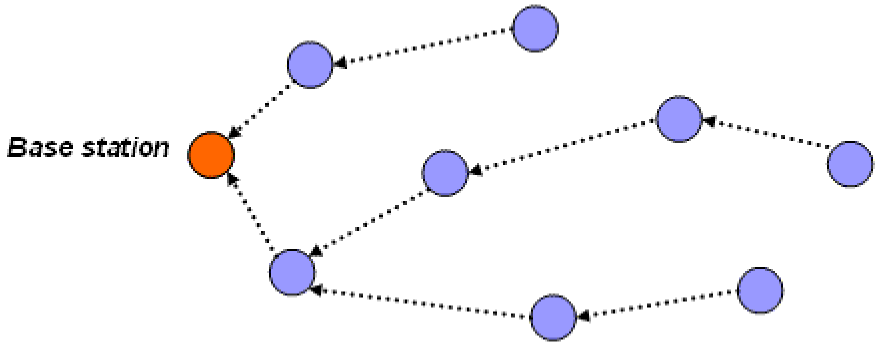
The scope of this research is to propose the information gathering system for the surveillance system to use in data delivery. In order to fit the requirements of the surveillance in section 2.2, the goals of the information gathering system are concluded as follows.

- The network establishment is economical in term of power consumption from data transmission.
- Information delivery is reliable.

Therefore, the contribution of this research on the surveillance system is to develop the information gathering system to provide an elemental service for the surveillance to gather data from sensors in the network. This includes both the network establishment at the initialization phase mentioned in section 2.4.1 and also the report delivery operation at the operation phase presented in section 2.4.3.

Not only for the surveillance system in this thesis, the information gathering is one of common but indispensable functions in other applications as well. Applications in WSNs mostly involve in monitoring the environment and gathering information from surrounding environment. Such a system is rather information-oriented than operation-oriented, so, most of applications involve in data accumulation. Although, being such an important and being urgently needed function, the information gathering is still lack of attention. When being implemented in real operation, the information gathering often become one of big weak points that lowers overall performance such as in [7] which reported the comparatively high loss rate of data during being transferred to the base station. The author also believes the loss caused from information gathering is still being ignored in other several projects due to time limitation and other more important special objectives.

Due to the fact that a mechanism to serve the information gathering is short of revising and the high demand of it in various areas of application using WSNs, this work intends to research the optimal way to implement information gathering service and develop a set of ready-to-use components for other WSNs application's developers to reuse and rapidly archive their projects' targets.



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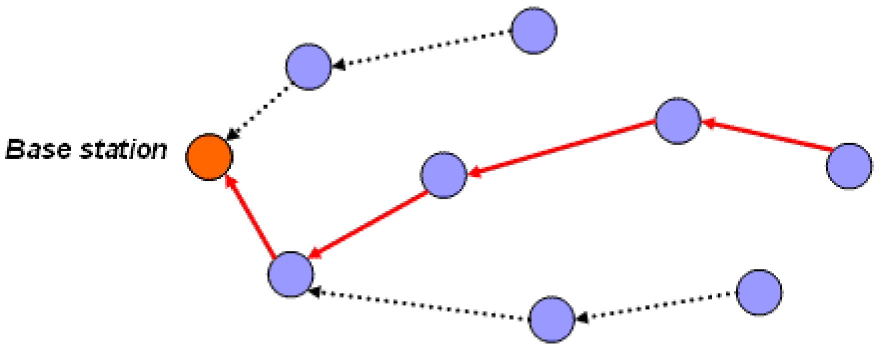


(b)

Figure 2.6: Many-to-one Routing Scheme:

(a) Spanning Communication Tree (b) Message forwarding

2.6 Concept of many-to-one Routing Scheme

From the design of communication route creation explained in section 2.4.1, the surveillance tries to construct communication routing paths to join all wireless sensors to the base station. The fundamental idea to supply this demand is building a spanning tree rooted at the base station and extending the tree throughout the network of sensors. When a sensor node is triggered to report any information to the base station, it merely transmits data to its parent node and intermediate nodes keep receiving and forwarding to their parents in a repetitive manner until the information reaches the top parent which is the base station as also demonstrated in figure 2.6. This kind of communication scheme is a many-to-one messaging system from all sensor nodes in a sensor network to the single destination, the base station.

Using the communication spanning tree is simple and effective if midway wireless sensors on each communication hop along the routes are well responsible for their packet forwarding duty. This raises following issues that must be considered to enhance efficiency of data delivery.

First, communication links along routing paths must be strictly selected. According to the fact that overall competence of information delivery totally relies on the quality of each communication links, therefore the link selection, in another word the parent selection at the network initialization plays a big role to overall performance of data delivery. A sensor node needs to find a good parent node which locates nearer to the base station and had a communication link in good condition connecting them together.

Second, the routing must tolerate unpredictable failures. Due to the nature of WSNs which may operate in critical environment, the characteristic of communication topology may change at any time and if no counter plan prepared, the system could get more damage.

2.7 Related Works on Many-to-one Communication System over WSNs

For the survey, we found 2 different methods to implement the many-to-one communication system over WSNs. All of them put emphasis on the parent selection process. The first approach tries to determine the quality of communication link and the parent node is elected based on use the result of link estimation. Another approach builds a communication tree by flooding a special route-creation packet from the base station and sensor nodes maintain reverse routes back to the root by assigning the sender of the first incoming route-creation packet to be the parent node.

In this thesis, a term “*Beacon Packet based Routing System (BP)*” represents a system working in the first manner and a term “*Simplified Directed Diffusion based Routing System (SDD)*” represents the second, respectively.

```
typedef struct TableEntry {
  uint16_t id;  // Node Address
  uint16_t parent;
  uint16_t missed;
  uint16_t received;
  int16_t lastSeqno;
  uint8_t flags;
  uint8_t liveliness;
  uint8_t hop;
  uint8_t receiveEst;
  uint8_t sendEst;
} TableEntry;
```

Figure 2.7: Neighbor Table used in BP-based Routing System

2.7.1 Beacon Packet based Routing System (BP-based Routing System)

Beacon Packet Based Routing System uses an adaptive multi-hop routing developed by Woo [8]. This method determines the communication link quality by broadcasting beacon packets. The link estimation is performed by counting lost beacon packets from sequence number and calculating an approximate quality of links connecting nearby sensor nodes. Beacon packets are also used for exchanging of information between neighbors that is essential information for parent selection such as *hop count*, a unit of distance from the base station in communication hop.

Each sensor node sends the beacon packet once every presetting certain interval and also collects the beacon packets from neighbors simultaneously. The sensor node updates information at neighbor table which contains parameters for being used in the parent selection. The structure of neighbor table is as depicted in figure 2.7. At the moment a sensor node receives the beacon packet, it searches for a record contains information from the sender and updates last sequential number, hop count, *liveliness* and *send estimation* in the neighbor table. After that, if it reaches the end of recalculating cycle, the sensor node calculates other secondary attributes including to *receive estimation*.

Receive estimate represents the quality of incoming communication link from each individual neighbor. The attribute can be calculated by counting the number of packet loss of incoming beacon packets. This figure is derived from the sequence number of a beacon packet. In contrast, due to the fact that a node can not identify packet loss rate in outgoing direction by itself, *send estimation*, which represents the quality in outgoing direction to neighbor nodes, can not be calculated without cooperation from neighbor nodes. For this reason, while transmitting a beacon packet, sensor nodes put their *receive estimation* values to payload of the beacon. The receivers search for their address from the beacon packet and copy the *receive estimation* to the neighbor table as their *send estimation*. By this scheme, sensor nodes are able to determine which neighbor nodes can receive data transmitted out from them with low packet loss rate. Lastly, *Liveliness* represents activeness of a sensor node. The BP-based routing system measures the activeness of sensors by beacon packets. Since a transmission rate of beacon is predefined, if the beacon packet does not arrive in expected period, a sensor node reduces a confidence of links. The *receive estimation* is calculated by following equations:

$$NewreceiveEst = \frac{255 * received}{missed + received}$$

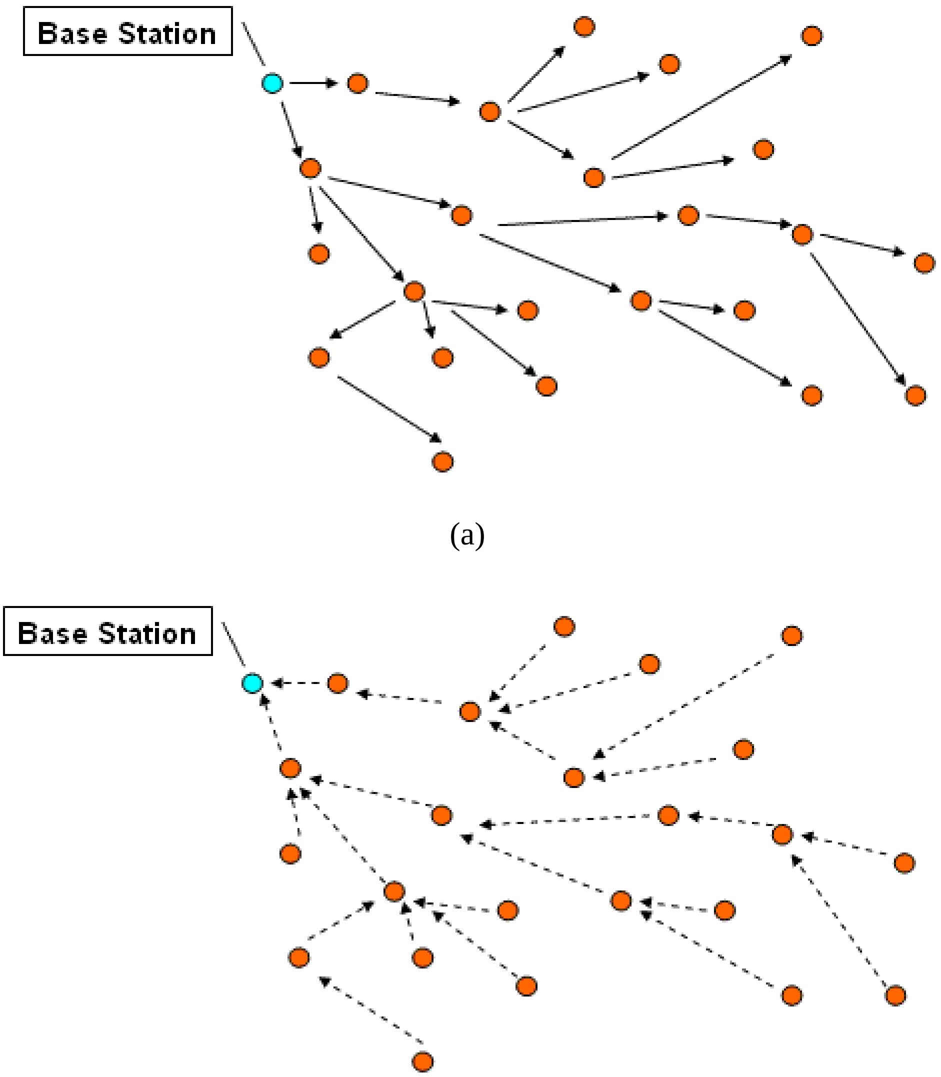
$$NewreceiveEst = \frac{NewreceiveEst}{2}; if\ (liveliness < MIN\_LIVELINESS)$$

$$receiveEst = \frac{receiveEst + 3 * NewreceiveEst}{4}$$

The *receive estimation* is periodically recomputed and the number of received, missed beacon packets and the *liveliness* value are reset after being calculated.

The information gathering is the one-way communication paradigm. Efficiency of delivery depends on data transmission from slave to parent node. For this reason, the *send estimate* attribute is used to determine the quality of link in parent selection. Another parameter is the hop count. In the BP-based routing system, a wireless sensor chooses a node which has the smallest hop count and has the best *send estimation* in case multiple nodes have the same hop count to be the parent node.

The BP-based Routing System has currently been used in a habitat monitoring WSN on the Great Duck Island by Szewczyk et. al. [9].



(a)

(b)

Figure 2.8: Simplified Directed Diffusion based Routing System:
(a) Route-creation packet propagation (b) Parent assignment

2.7.2 Simplified Directed Diffusion based Routing System (SDD-based Routing System)

In contrast to BP-based routing system, Simplified Directed Diffusion based routing system eliminates the link estimation. From the observations, applications over WSNs, which give high level of consideration on the energy-consumption issue, are mostly designed to cut the link estimation out, for example, VigilNet by He and et al. [7]. In the SDD-based routing system, the network is constructed by applying the similar technique used in Directed Diffusion [1] to create a routing tree.

This algorithm is simple and effective especially in term of energy conservation. First, the base station broadcasts the route-creation packet and sensor nodes which receive the route-creation packet maintain an address of the base station as their parent node. Receivers continue forwarding the route-creation packet and this cycle is executed recursively until the flooding packet spreads throughout the network. A sensor node basically chooses a parent based on the source address of the first flooding packet that it receives. Figure 2.8 illustrates

BP-based and SDD-based routing systems are both trying to answer the same question which is to create the routing tree rooted at the base station and cover the sensor network. Each node has one own parent which is the next-hop destination when delivering report. The biggest difference is the mechanisms to address a parent node, the parent selection.

High packet-loss rate caused from the asymmetric phenomenon of links is expected to be the unavoidable problem. In SDD-based routing system, sensor nodes choose parents by considering the link quality in reversed direction, in other words, the incoming direction not outgoing direction which is actually going to be used.

In VigilNet [6], the developers evaluated the Reinforcement message technique in Directed Diffusion [1] or link-layer handshaking were both too expensive to remove the asymmetric links circumstance; they tried to use a cheaper strategy by transmitting data in low power sitting at the network establishment phase and sending data in maximum level of power during the operation phase. Setting to lower transmission power is expected to ensure that only nearby neighbors would receive the route-creation packet. And when transmitting application data during operating, the maximum of transmission power would ensure accomplishment of information delivery along the diffusion tree.

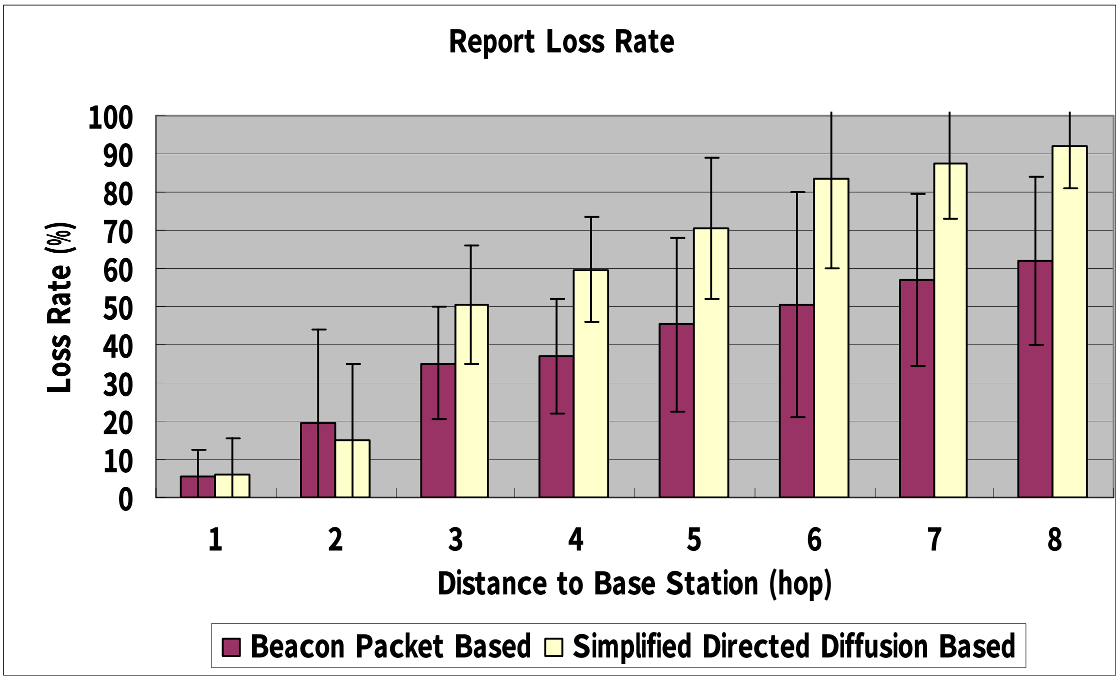
Chapter 3
System Design for Information Gathering over WSNs

The previous chapter introduced an overview of the surveillance system using WSNs and current widely used implementations of the information gathering. This chapter studies in depth on the information gathering. In order to understand the performance and current problems of the current works, the performance evaluation is conducted and shown in section 3.1. After address the limitations, this chapter introduces the Handshaking to enhance the quality of network establishment in section 3.2 and section 3.3 proposes the Packet Link Layer to strengthen fundamental communication links by the Data Retransmission. Finally, the proposal of dynamically changing the routing paths is presented in section 3.4

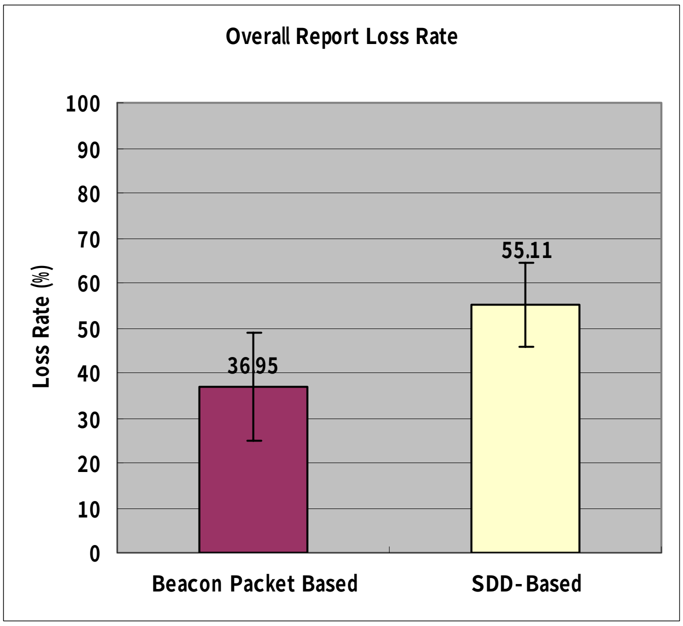
3.1 Performance Evaluation of Current Works

In order to conclude the actual performance, this subsection evaluates the current works including BP-based and SDD-based routing systems. The simulation was performed on TOSSIM which are described in section 4.1. In the simulation, 49 sensors were deployed to a rectangular grid with 10 feet spacing as can be seen in figure 4.2. Other configuration was set corresponding to explanation in section 4.1.1 and the empirical radio loss model in figure 4.1 was applied to simulate the characteristic of communication links. The network establishment process was implemented by Beacon Packet-based methods presented in section 2.7.1 and Simplified Directed Diffusion-based methods described in section 2.7.2. The object monitoring system was simulated 30 times for each approach. The objective of this evaluation is to compare efficiency of *report* delivery and overhead of data transmission between these 2 approaches. Note that the definition of special words such as "*report*" is described in section 4.2.

3.1.1 Simulation Result



(a)



(b)

Figure 3.1: Report Loss Rate in Previous Works:

(a) Report Loss Rate categorized by distance from a sender to the base station

(b) Overall Loss Rate

Figure 3.1 (a) shows the *report* loss rate of each report delivery approach. The result shows that the loss rate grows in proportional to the distance between a *report* originator to the base station. The BP-based approach comparatively provided better reliability than SDD-based approach, especially for wireless sensors deployed at more than 6 hops far from the base station, the loss rate climbed up to more than 80 percents. However, the BP-based method also disqualified to service the dependable *report* delivery; more than 30 percents of *reports* submitted from nodes placed further than 3 hops got lost.

Figure 3.1(b) concludes the overall loss of *report* in the simulation. The loss rates were 36.95 percents in BP-based approach and 55.11 percents in SDD-based approach. This leads to the conclusion that both of 2 methods greatly suffers from the high loss rate issue and can not be used without modification.

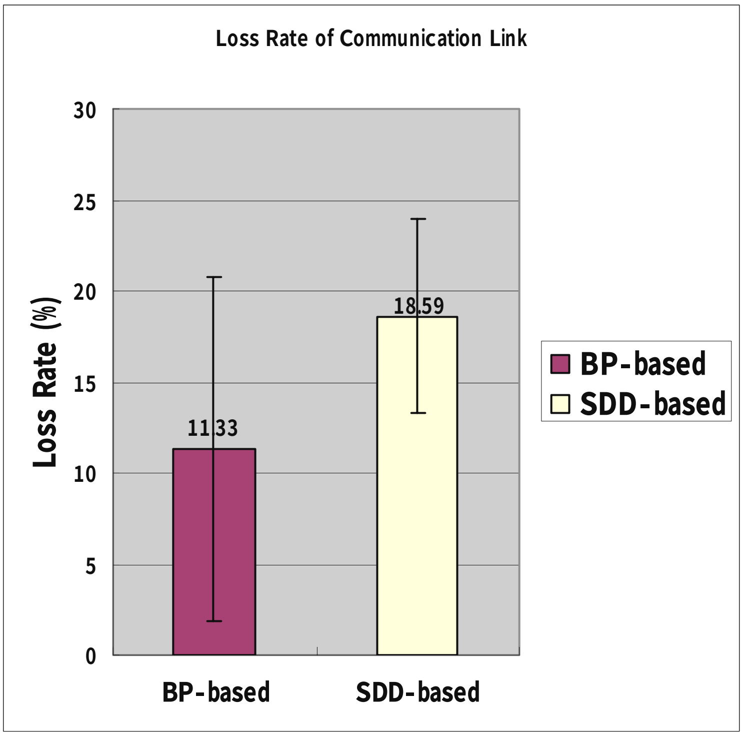


Figure 3.2: Loss Rate of Communication Link in Previous Works

Figure 3.2 shows the average quality of communication links being selected in the network establishment phase. The object monitoring system used different techniques in the simulation to choose the parent node. According to the result, the

BP-based approach performed better in the parent selection process. The distribution of results is still high due to the extremely high variation of communication links as shown figure 4.1; however, the average loss rate of each link in BP-based approach is 11.33 percents lowers than 18.59 percents of loss rate for each data transmission in SDD-based approach.

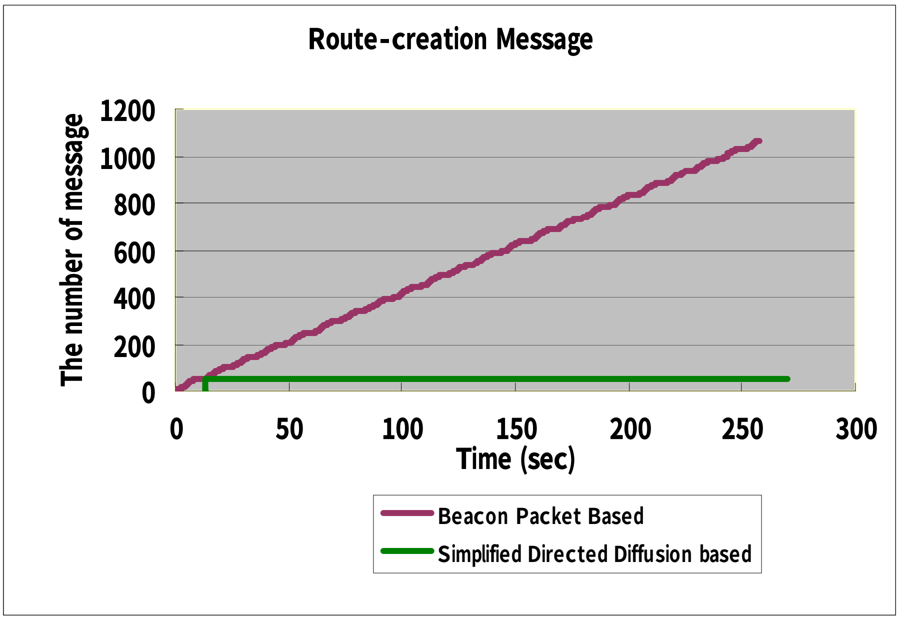


Figure 3.3: Data Transmission in Network Establishment in Previous Works

The number of *route-creation* message transmitted from all sensor nodes was counted to represent data transmission overhead. Figure 3.3 shows 2 completely different shapes of graph. The SDD-based approach sends out the *route-creation* messages within short time period to create the network; the transmission stopped after the spanning communication tree spanned entire wireless sensor nodes. The number of *route-creation* message is static 49 packets corresponding to the number of sensor node.

In contrast, The BP-based approach transmitted a number of route-creation messages in term of the beacon packet to estimate the communication links quality. Because the beacons were broadcasted at a certain rate, beaconing every 12 seconds for this simulation, then the number of *route-creation* message developed continuously at a rate 400 messages per 100 seconds. Since an object started moving in the operating area at 50 time point and be in the network of wireless sensors for 200 seconds, the total number of *route-creation* message is approximately 900-100 messages.

3.1.2 Limitations of Previous Works

The evaluation shows that both BP-based approach and SDD-based approach still produce high loss rate of *report* delivery. Furthermore, the BP-based approach consumes much energy on the link estimation in particular. According to the evaluation, the beaconing in BP-based approach costs 400 messages per 100 seconds of operating and the only one way to decrease is reducing the beaconing rate. However, the reduction will result in much longer delay in network establishment. Moreover, it also affects the capability to respond to dynamic change of communication links which is an important advantage of using BP-based approach. Therefore, the BP-based approach is considered not flexible to be modified.

On the other hand, the SDD-based approach is satisfied the requirement to conserve energy. Sensor nodes can establish a spanning routing tree within one packet flooding. Nevertheless, since sensor nodes are lack of understanding actual properties of communication links; the parent selection process are too greedy, so, some bad links are sometimes selected which cause high loss rate of data transmission. The evaluation shows a need of improvement at quality of service if SDD-based approach will be used to serve the *report* delivery.

3.2 Proposal of applying the Handshaking to Network Establishment

The evaluation in section 3.1 showed limitations of both 2 previous works. BP-based approach consumes much power from the beaconing in the link estimation. This opposes the primary goal of this research and constraint of WSNs which the application must run in energy-efficient manner. In contrast, SDD-based routing system which costs relatively much lower data transmission during the network establishment encounters the high packet loss’s problem. The SDD-based routing system fails to deliver data especially if a sender locates further from the root.

The main cause of high data transmission in BP-based routing system is the design which enforces sensor nodes to transmit the beacon packets in certain interval.

In ideal paradigm of routing system, data transmission is executed only when there are data to transmit, or in this surveillance system's case, there are reports which wireless sensors want to deliver to the base station. For the design of BP-based method, the beaconing is for maintaining communication links to be always in good condition. Although it allows sensors to always be ready to send the report to the base station, keeping on exchanging the beacon packets in this process of a case that no any event is tracked, no any report is about to delivery can also be considered as a waste of energy. In ideal model, there should be no data transmission at all unless there are things to deliver.

Only one solution to reduce data transmission in the BP-based routing system is decreasing the beaconing rate. This parameter can be adjusted before compiling the application. However, adjusting the beaconing rate possibly affects a lot of other functions. As the key parameter in BP-based routing system, reducing the beaconing rate extremely extends the length of time used for the network establishment. The spanning communication tree expands slowly hop by hop in BP-based routing system. A sensor node connects to the routing tree by selecting the parent node only after it has kept information about the quality of links by exchanging of beacon packets for some time. So, enlarging interval between each beaconing makes time for the network construction to cover the whole sensors become longer. Moreover, the ability to quickly response to change of link's properties, which is one of the major advantages, will get more insensitive. For these reasons, BP-based method is not flexible enough to be modified in order to reduce the data transmission.

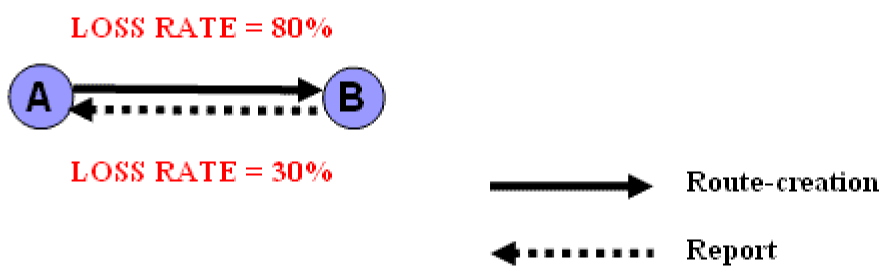


Figure 3.4: Asymmetric phenomenon of communication Link

On the other side, SDD-based routing system satisfies the ideal model in term of energy consumption. SDD-based method is event-driven; it starts data transmission only when sensor nodes have report to submit to the base station. However, the outcome of using the greedy way in the network establishment is that the quality of routing paths is sometimes bad. The reasons why some bad communication links were selected can be concluded as following:

1. No link check: sensor nodes immediately assign the parent after they accept the route-creation. That is actually not enough to guarantee whether the link is in good condition; it might be a bad link and the successful transmission was the lucky case happens once in hundred times of trial.
2. Asymmetric phenomenon of communication links: As also reported in [7], communication links are possibly asymmetric in a real world. This makes the SDD-based method, which is not concerned on the quality of link, produce worse result. As seen in figure 3.4, the sensor node receives the route-creation packet in an incoming direction and entrust itself that the link should be also in good condition in an outgoing direction too. This results in high packet loss rate in a case as shown in figure 3.4 where the communication is good in an incoming direction but very bad in the reverse way. The packet transmission then tends to be failed when the sensor transmits the report via this kind of links.

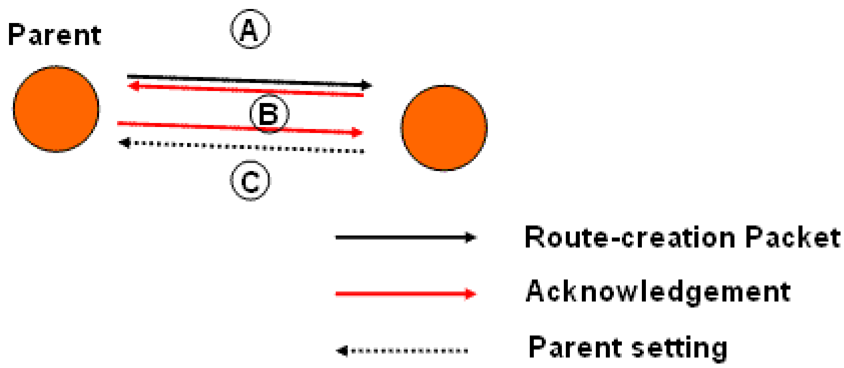


Figure 3.5: Handshaking in the parent selection

The weak point of SDD-based algorithm is the parent selection. The evaluation and analysis showed that it was impossible to get accuracy in the parent selection without the quality estimation. Therefore, SDD-based routing system is expected to work in higher level of reliability if being added a process to check candidate links before choosing and handshaking is considered an appropriate answer.

The handshaking will be inserted during the route-creation propagation as shown in figure 3.5. The new sequence of parent selection will be like these:

A. After the sensor nodes receive the route-creation packet , they reply the sender with the acknowledgement
B. The sender replies back the ACK message.
C. If the sensor receives the reply of its acknowledgement, set the sender to be the parent node.

The handshaking is simple and cheap. It also contributes in eliminating the data loss caused by the asymmetric phenomenon since the handshaking requires data transmission in both incoming and outgoing direction. The handshaking performs as light-weight link estimation.

The network periodically resets so that communication links which have turn bad can be removed [7]. The original SDD-based method is static. Although this thesis proposes the Dynamic Route Alteration to deal with broken links in section 3.4, the network resetting is considerable useful as a secondary counterplan. Furthermore, it also supports the Dynamic Route Alteration in controlling the quality of service which is explained later in section 3.4.

For the energy issue, the handshaking costs at least more than 3 times than original version during the network establishment. However, comparing with BP-based routing system, this increment by the handshaking is relatively small and negligible. The performance evaluation in section 4.3 describes more detail on this issue.

3.3 Data Retransmission in hop-by-hop Communication Level

The new approach of parent selection with the handshaking explained in previous section enhances the quality of network by avoiding bad communication links, in other words, trying to use available resource as efficient as possible. This section proposes a more offensive method under the way of thinking that if available resources are not good enough, there is no another way else except making the limited resources better.

The evaluation of a system with handshaking in the parent selection in section 4.3 shows remaining of data loss rate. The cause is that the network still consists of some bad communication links which makes the reports get loss during being delivered. Since the parent selection concerns only the network construction, the loss of information during the operation needs another mechanism. If the problem is that the system is using links which are bad, we have 2 ways to settle.

First, stop using those bad links and change into better ones that motivates the author to propose the Dynamic Route Alteration in section 3.4.

Second, strengthen the bad links by repeating transmission of identical message on each of communication hop along the routing path. This thesis applies both 2 approaches to tear down the report loss and this section firstly explains the fault tolerance by redundancy transmission.

The redundancy transmission can be classified to 2 types. In the first type, the number of redundancy transmission is fixed beforehand and a sender sends identical message many times equals to the setting. For example, if a sender is arranged to send 3 redundant packets in order to deliver 1 message, at every hop of communication routing paths, 3 packet containing the same information will be sent out so that the probability that the receiver gets at least 1 packet will become larger. This is the way retransmitting the same message many times strengthens the communication links.

This type of redundant transmission is simple for implementing and can be easily analyzed the overhead cost of redundant transmission because it is static. In basically, 1 *report* requires only 1 *report* message to cross each hop. So, the base cost of delivery is 1 data transmission. If a sensor node is set to repeat 3 times of transmitting 3 identical packets, the overhead then is 2 packets.

However, this static redundant-transmission paradigm is short of flexibility and adaptiveness. Since the number of transmitting packets with the same content is predetermined, it turns out to be possibly too wasteful especially when delivering the report through links which are in very good condition. The number of redundant messages should be proportional to the quality of links which, by this static scheme, is impossible.

In order that the redundant transmission fits actual property of each communication link, a sender needs a feedback from a receiver to determine the number of packet retransmission. As the method used in various routing protocols such as TCP/IP, the message acknowledgement is considered to be used to provide the response from the receiver to the sender. A receiver replies the acknowledgement packet to a sender and the sender keeps retransmitting the retransmission packet until it gets the acknowledgement or reaches the maximum retransmission number (Max RT).

Besides strengthening the quality of each single-hop communication link in the multi-hop routing paths, Data Retransmission also indirectly provides the link estimation. Since the packet acknowledgement enables a sender to recognize the result of data transmission, this information is collected as the history of transmission, in other words, the link quality estimation, and can be used in other parts of routing system. Similarly to the idea in BP-based routing system, the best way to estimate the quality of communication is sending real message and measuring the result. So, data retransmission and message acknowledgement both play important role in link strengthening and link estimation.

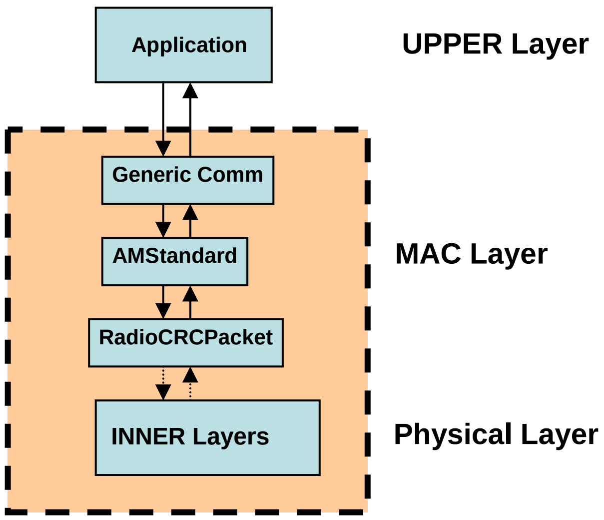


Figure 3.6: Networking Stack in TinyOS

There is one of design point left, however, can not explain without demonstrating the current structure of networking stack in TinyOS. As shown in figure 3.6, TinyOS, an operating system for WSNs, allows developers to freely design one's own routing system. The operating system provides only components in charge of single-hop communication whose inputs are address of a destination node and message. These components are ones in the MAC layer in figure 3.6; they get a command to send a message from upper-layered components and perform the data transmission without any guarantee of delivery. On the other side, developers are forced to implement a whole multi-hop routing system themselves. And the prototype of routing system is presented in section 3.1.

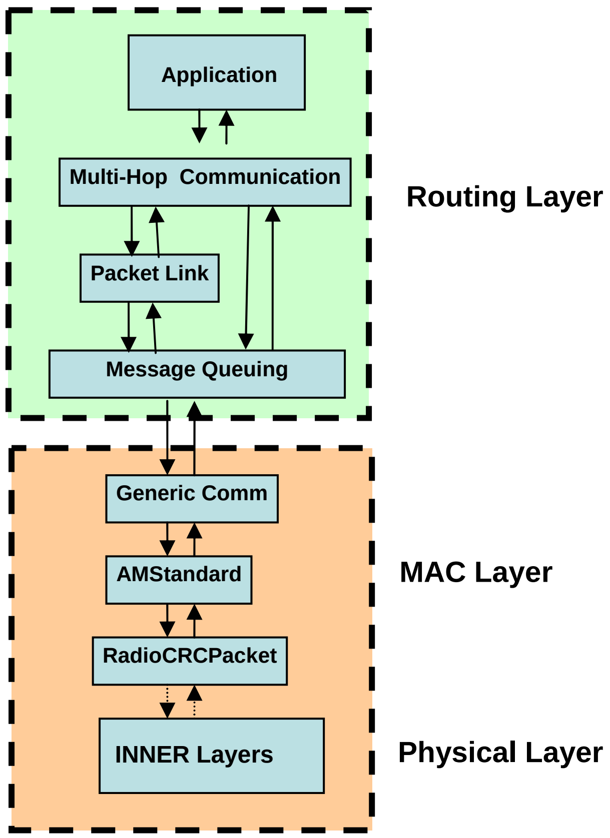


Figure 3.7: Structure of Networking Stack in this thesis

Figure 3.7 shows the structure of routing system in this thesis; *Multi-hop Communication* component in figure 3.7 is in charge of report delivery both the network establishment process and message forwarding. There is a use of *Message Queuing* component as a queue controller because *Generic Comm* component, which is a component in control of single-hop communication, can process only one packet transmission for any moment. TinyOS has 256 channels of data transmission or 256 types of message. *Generic Comm* component will make sure that only a couple of sending side and receiving side connecting the same channel can exchange messages each other. However, *Generic Comm* component, or single-hop communication component, refuses to transmit or buffer any sending request if it is busy on transmitting another packet, even though the message type is not the same. For this reason, *Message Queuing* component is in charge of arranging messages to be passed into *Generic Comm* component one by one.

Lastly, *Packet Link* component represents a component in control of packet link layer which is described the expectation in [10]. In conclusion, the Packet Link Layer is defined to be responsible for providing error correction functionality in Data Link Layer of OSI model. And in this research, the data retransmission is implemented in this layer. The Packet Link Layer is regularly between Network Layer and Data Link Layer. However, as illustrated in figure 3.7, only some channels are connected through *Packet Link* component and others are directly connected from *Multi-hop Communication* component to *Generic Comm* component. The structure of networking stack is designed in this way because only a portion of transmission channel is expected to be strengthened.

As the technique used in [7] which the data transmission power is decreased during the network construction so that only truly good communication links are selected in the parent selection process. And the power setting is increased to the highest level during the operation in order that reports are delivered with high quality, low loss rate. This work also applies the same technique to enhance the parent selection, however, in different way of implementation. Instead of adjusting the transmission power, this surveillance system makes use of the *Packet Link* component only at transmission channels being assigned to deliver the report. Data transmission in channels allocated for network construction's purposes, such as the network establishment and Dynamic Route Alteration, will not be corrected by Packet Link Layer. This implies that the quality of same communication links is lower during operations related to the network construction but higher during the report delivery by the data retransmission mechanism in the Packet Link Layer.

3.4 Dynamic Route Alteration (DRA)

Data Retransmission stated in section 3.3 unquestionably reduces some levels of the loss rate of packet on each hop-to-hop communication link. Although the Data Retransmission can alleviate the loss of packet along the routing path created since the network establishment, occurrences of packet loss still exists on bad communication links which were fortunately selected or had ever been in good condition but turned into bad link because of environmental factors. In these cases, the system needs a mechanism to dynamically change the forwarding route and Dynamic Route Alteration is proposed for this reason.

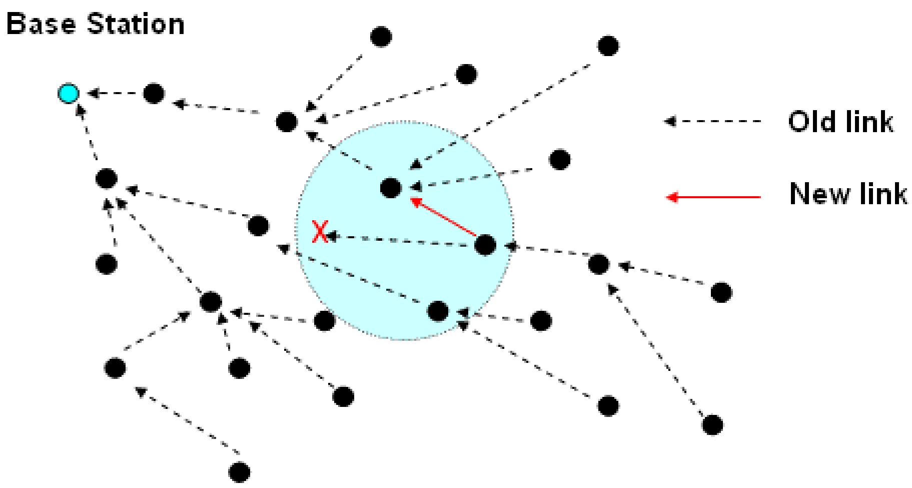


Figure 3.8: Overview of Dynamic Route Alteration

According to the current design, we can expect that every sensor node is linked to the spanning routing tree. Therefore, the Dynamic Route Alteration can be simply implemented by letting a sensor node changing its parent node to another node whose communication link between them is in good condition as shown in figure 3.8. The next important issue is when the Dynamic Route Alteration is executed. As a trigger switch of starting the Dynamic Route Alteration, data transmission failure in Packet Link Layer activates the sender to change the parent. The Packet Link component enables components in upper layer to recognize if the requested transmission is failed or succeeded. Thus, Dynamic Route Alteration is invoked when the routing layer is reported that the data transmission was unsuccessful.

When a sensor node decided to perform the DRA, it searches for a candidate of being its new parent node and sends a request-to-connect message to that candidate node. The request-to-connect message acts in the same way as the acknowledgement of the route-creation packet does during the network establishment phase. If the candidate accepts the request-to-connect message, it replies to the sender of the packet with an acceptance message. The requestor waits for the acceptance message from the requested candidate for a certain time period; the node sets the candidate to be the new parent node in case that the acceptance arrives in time, or repeats since the candidate searching process otherwise.

For the rule of candidate selection, the sensor sets priority by the quality of communication link which connects the node and a neighboring node. A neighbor node having the highest link quality will be first picked out and if the Dynamic Route Alteration fails for this candidate, a node in a next sequence will be chosen. In case there are multiple candidates having the same link quality, the node having smaller *Hop count* is selected. The information of link quality is provided by the Packet Link Layer. As presented in section 3.3, the Packet Link Layer returns the transmission command with the result so the routing layer can preserve this information in the *neighbor table* which is constructed from the network establishment phase.

The reasons why the DRA uses the quality of communication link as the rule in the candidate selection are first, to find a route which is in a good condition as the first objective of DRA and second, to reduce time delay cost by the Dynamic Route Alteration. The more probability that the request-to-connect process fails, the longer time the Dynamic Route Alteration needs for repeating the candidate selection and the request-to-connect process. The evaluation in section 4.5 showed a big correlation between delay in the DRA and performance of message forwarding which will be later discuss in section 4.5. For this reason, it is significant to complete the Dynamic Route Alteration as fast as possible.

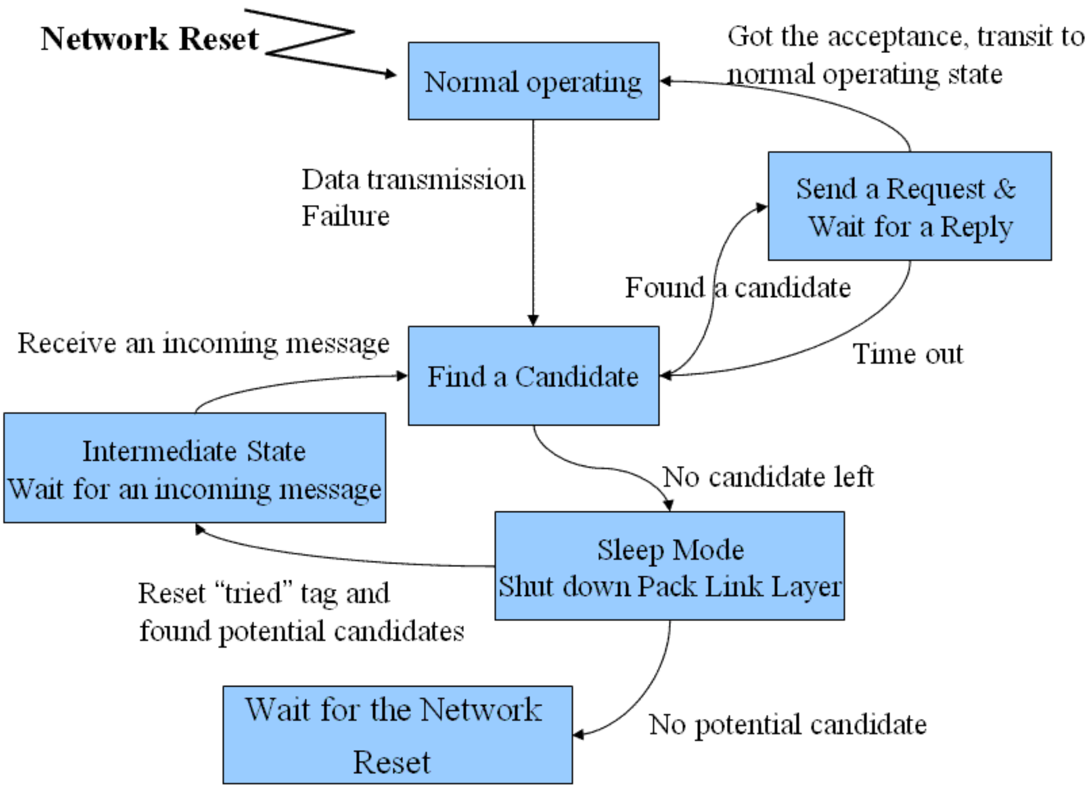


Figure 3.9: State Diagram of Dynamic Route Alteration

Flow chat of Dynamic Route Alteration is shown by a state diagram in figure 3.9. The DRA starts when data transmission fails; the status of a parent node in that moment in the neighbor table is changed to “TRIED” tag and a value in a *Penalty* column is increased one before DRA transits to a state that the sensor node tries to find a candidate of being a parent from the neighbor table. The potential candidate must be:

A). A node which has a “NORMAL” tag in a status column of the neighbor table.

B). A node whose value in a *Penalty* column does not exceed *Maximum Penalty*.

C). Having less than or equal *Hop count* to current hop count in order to prevent a cycle in routing tree.

If the sensor node can find a qualified node to be the candidate, the request-to-connect message is sent to the candidate and the sender waits for an acceptance. When the acknowledgement of the request-to-connect message is replied, the sensor node sets the candidate to be the parent and transits to a normal operating state again; if not, the sensor sets a status of the candidate in the neighbor table to “TRIED” tag and repeats all processes since seeking for next candidate again.

If all possible neighboring nodes have been tagged with “TRIED” and the sensor node can not find a qualified node, it transits to a temporarily sleep mode. While the node is in sleep mode, the Packet Link component is shut down to stop responding to incoming messages. This is an indirect command to order child nodes, which keep transmitting messages in, to look for new parent nodes. Therefore, the length of sleeping must be at least longer than a time period that child nodes wait for the acknowledgement at the Packet Link level. For example, if the *Maximum Retransmission* is set to 2 and the retransmission timeout is set to 500 milliseconds, the length of sleeping period in DRA must be longer than 500 + 500 + 1000 (*exponential back off*) = 2 seconds.

When the node wakes up, it clears all “TRIED” tags in a status column to “NORMAL” and checks if there is at least one qualified node left in the neighbor table. The node goes to a complete sleep state if it has no possible parent node and stay still in this state until the network resetting, in other words, the route-creation message is broadcasted again. Otherwise, the node transits itself to an intermediate state turning on the Packet Link Layer and waiting for incoming message. The sensor node does not immediately perform the parent requesting process to avoid infinite cycles of sleep and wake up and request. The node starts finding a candidate again after being triggered by new incoming message.

In conclusion, there are 3 significant parameters in Dynamic Route Alteration. The first one is *Maximum Penalty*. If this value is set to be bigger, sensor nodes will put more effort to contribute to the report delivery. However, it also makes sensor node, which are not in a good condition to contribute the report delivery, stubborn to stop operating.

The second one is timeout of waiting an acceptance message. The acceptance timeout must be at least longer than the round-trip time which relies on hardware of radio transceiver.

The last parameter is an amount of time in the temporarily sleep mode.

Chapter 4
Simulation Performance Evaluation

The previous chapter introduces 3 proposals to improve performance of information gathering including applying the handshaking technique to the network establishment phase, strengthening communication links at hop-by-hop communication by the Data Retransmission and using Dynamic Route Alteration. This chapter shows performance evaluation which is conducted on TOSSIM [11]. TOSSIM is the most widely used simulation for WSNs in recent years.

This chapter is organized as follows. In section 4.1, the simulation environment including evaluation method, TOSSIM and the radio loss model in the simulation are described and section 4.2 explains metrics of the evaluation and defines specific words used in this thesis to represent each types of message. Section 4.3 shows the performance evaluation of using Handshaking and section 4.4 describes the performance evaluation of the Packet Link Layer and the performance evaluation of Dynamic Route Alteration is shown in section 4.5. Finally, section 4.6 discusses on the system configurations.

4.1 Simulation Environment

4.1.1 Evaluation Method

In order to evaluate the performance of each proposal, we developed a simple object monitoring system. The monitoring system operates over the network of wireless immobilized and densely deployed sensors as assumptions mentioned before. The system did a simple surveillance by inspecting for an object within each wireless sensor' sensing range and individually submits the *report* to the base station if the object is detected.

The monitoring system starts working by first establishing the network to connect all wireless sensors together. This network is to be subsequently used for delivering *reports* to the base station. After the network construction is completed, the sensors stand by for intruding objects.

In the simulation, an object will enter operating region and moved slowly for 200 seconds. We scheduled the moving path of the object in a manner that all wireless sensors were able to find the object. Each node investigates an object every 5 seconds and the sensing range of sensor is set to 10 feet.

The proposals are evaluated through the monitor system for the reason that we can examine the behavior of the protocol in several circumstances that possibly happens in real-world operation. For example, a case that an object is detected by multiple sensors at the same moment that causes the radio communication around the object busy on reports' submission. Therefore, evaluating the performance of a communication protocol in the real operation can reflect the actual performance rather than partly testing only the communication module.

4.1.2 TOSSIM

The object monitoring system was simulated on TOSSIM, a simulator for TinyOS applications [11]. TOSSIM can emulate actual application code without a need of code modifying. It is designed specifically for TinyOS applications to be run on MICA Motes [12]. The developers of TOSSIM had 4 key concepts as following:

- *Scalability*: the system should be able to handle thousands of nodes with different network configurations.
- *Completeness*: as many system interactions as possible must be covered in order to accurately capture behavior of applications.
- *Fidelity*: subtle interactions must be captured if testing is to be accurate.
- *Bridging*: validating the implementation of algorithms

In order to achieve its goal of scalability, each node in the simulator is connected in a directed graph where each edge has a probabilistic bit error between 0-1. TOSSIM runs the same application code in all nodes. The architecture of TOSSIM is made up of a number of different components which support for compiling a network topology graph, a discrete event queue, simulated hardware and a communication infrastructure that allows the simulator to communicate with external programs like TinyViz [11]. Most application code is run unchanged except some components which interact with hard ware such as Led, Sensor, etc.

Additionally, TOSSIM has a visualization tool, a so-called TinyViz, to illustrate the simulation in form of graphical user interface. TOSSIM allows simulations to be visualized, controlled, and analyzed via TinyViz and TinyViz provides visual feedback on the simulation state and mechanisms for controlling the running simulation, e.g., modifying ADC readings and radio loss probabilities. Moreover, it also provides a plug-in interface allowing developers to implement their own application-specific visualization and control code. In order to simulate the existence and movement of an object in the simulation, we created and put a tracking plug-in to the TinyViz.

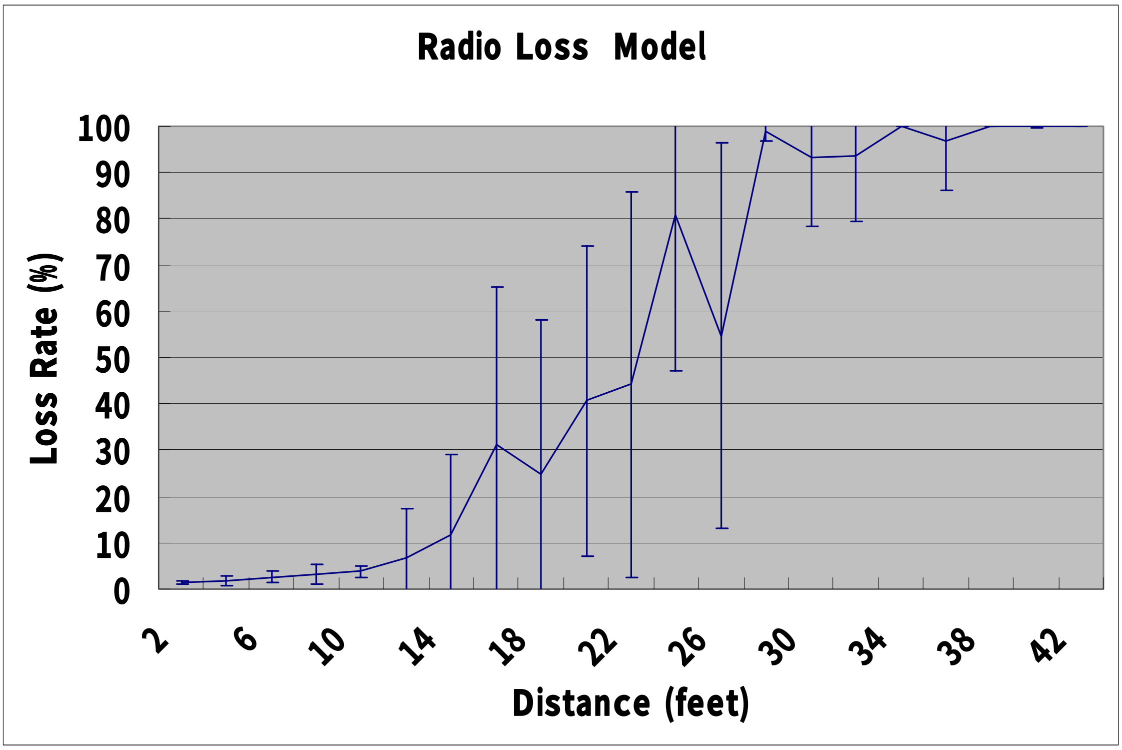


Figure 4.1: Radio Loss Model in TOSSIM

4.1.3 Radio Loss Model

The characteristic of radio communication in the simulation behaves as shown in figure 4.1. The model was generated based on statistical empirical loss data gathered from a real-world network [13]. The empirical data and Gaussian packet loss distributions is a function of distance. Given a physical sensor node topology, TinyViz generates connectivity for each wireless sensor pair by sampling these distributions.

4.2 Metrics used in Evaluation and Definition of Words

This subsection explains metrics used in the evaluation and definition of specific vocabularies used in this chapter. First, the following is a list of words used to name each type of message.

- *Report* represents information a sensor node in the network creates and submits to the base station. In this thesis, *Report* represents data of detected object which inside contains information including time, location, etc.
- *Report Message* stands for a message that delivers the *Report* through each hop of routing path. Note that the *Report Message* does not include other types of message such as *RT message*, in other words, it represents the first message transmitted out from a wireless sensor locating along the routing path to that sensor's parent node. So, a *Report* from a sensor deployed 4 hops far from the base station needs 4 times of data transmission of *Report message* to traverse the routing path.
- *Retransmission Message* *(RT message)* is a message transmitted by the data retransmission mechanism in Packet Link Layer. *RT* message is sent only in a case that a previous data transmission fails.
- *Dynamic Route Alteration Message* *(DRA message)* represents a message the Dynamic Route Alteration transmits in order to change the parent node during the operation phase.
- *Route-creation Message* represents a message transmitted in order to construct the routing communication tree during the network establishment phase.
- *Acknowledgement Message* *(ACK message)* is a reply message a receiver transmits back to a sender of *Report messages* or *RT message.*

Next, the metrics used to evaluation the performance of each design and configurations of information gathering system are concluded in following.

- *Report Loss Rate (By hop)*: this metric shows the correlation between a distance of a *report* sender to the base station and the loss rate of *report*.
- *Overall Report Loss Rate*: illustrates summary of *report* loss rate.
- *Loss Rate of Communication Link*: explains the average loss rate of communication links. It is an important variable to evaluate the performance of selecting communication links of each network construction methods.
- *The number of Route-creation Message*: shows overhead in network establishment to compare the data transmission cost.
- *Loss Rate in Packet Link Layer*: this is a loss rate of hop-by-hop communication which shows efficiency of data transmission after adding the Data Retransmission mechanism.
- *Overall Data Transmission per 100 Report Message*: exhibits all data transmission of any purposes which consist of *ACK* message, *RT* message and *DRA* message with respect to 100 *Report* message.
- *Factors of Report Loss in DRA per 100 Report Message*: presents causes of *Report* loss in Dynamic Route Alteration.

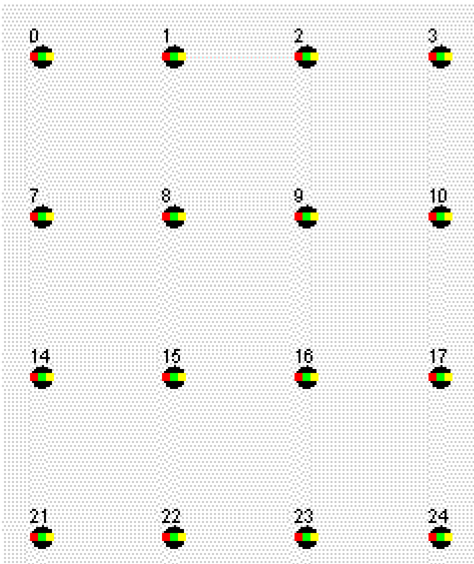
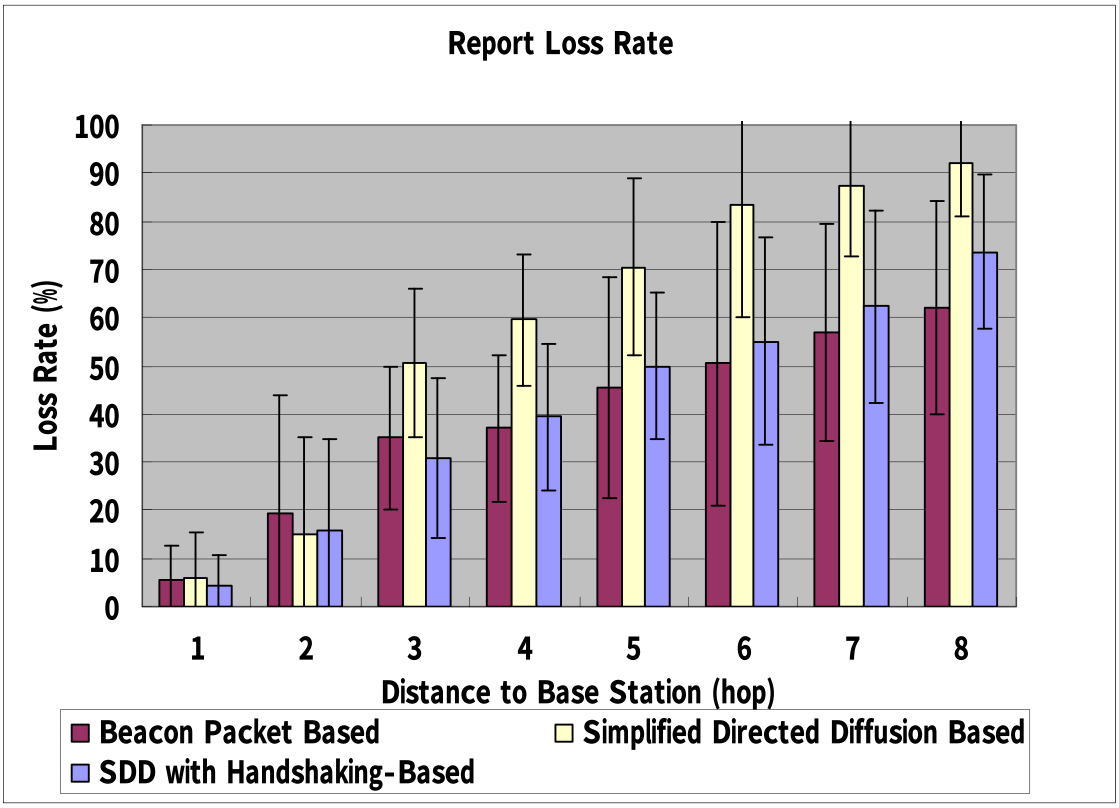


Figure 4.2: Rectangular Grid

4.3 Evaluation of SDD with Handshaking-based Approach

In order to show how much the Handshaking proposed in section 3.2 can enhance the parent selection in the network establishment phase of the SDD-based routing system, the evaluation of SDD with Handshaking-based approach is conducted. In the simulation, 49 sensors were deployed to a rectangular grid with 10 feet spacing as shown in figure 4.2. Other configurations were set as explained in section 4.1.1 and the empirical radio loss model in figure 4.1 was applied to simulate the behavior of communication links. The network establishment process was implemented on top of the SDD-based approach added the Handshaking to the parent selection process. The simulations were run 30 times.

4.3.1 Simulation Result



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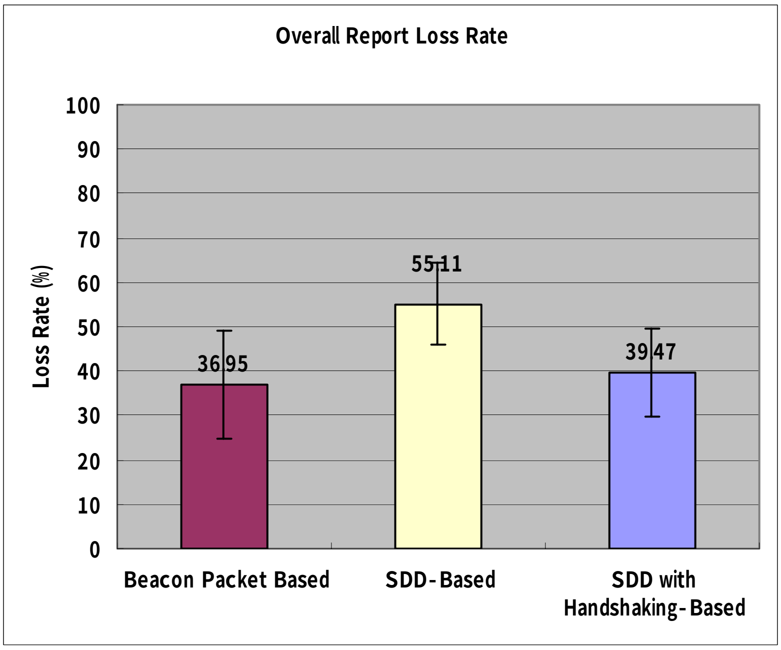


(b)

Figure 4.3: Report Loss Rate in SDD with Handshaking-based approach:
(a) Report Loss Rate categorized by distance from a sender to the base station
(b) Overall Loss Rate

The *report* loss rate of SDD with Handshaking-based approach is summarized in figure 4.3. Figure 4.3 (a) shows obviously that adding the handshaking makes the performance of parent selection improve in some levels. The SDD with Handshaking-based approach could deliver *reports* in lower loss rate than the original version, although it still produced slightly higher loss rate than the BP-based approach. The handshaking reduced the overall loss rate of *reports* from 55.11 percents to 39.47 or 28.38 percents of reduction. Even though the improvement is still not much enough to satisfy the target of this research, it indicates a good sign of enhancement.

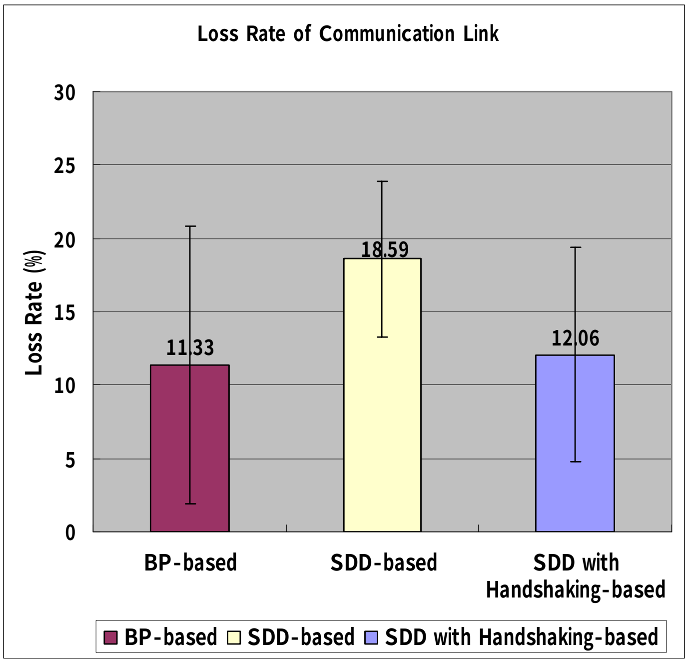


Figure 4.4: Loss Rate of Communication Link in SDD with Handshaking-based Approach

Figure 4.4 shows a proof that the SDD with Handshaking-based approach choose communication links whose quality is better than the SDD-based did. This result substantiates the performance improvement of the parent selection.

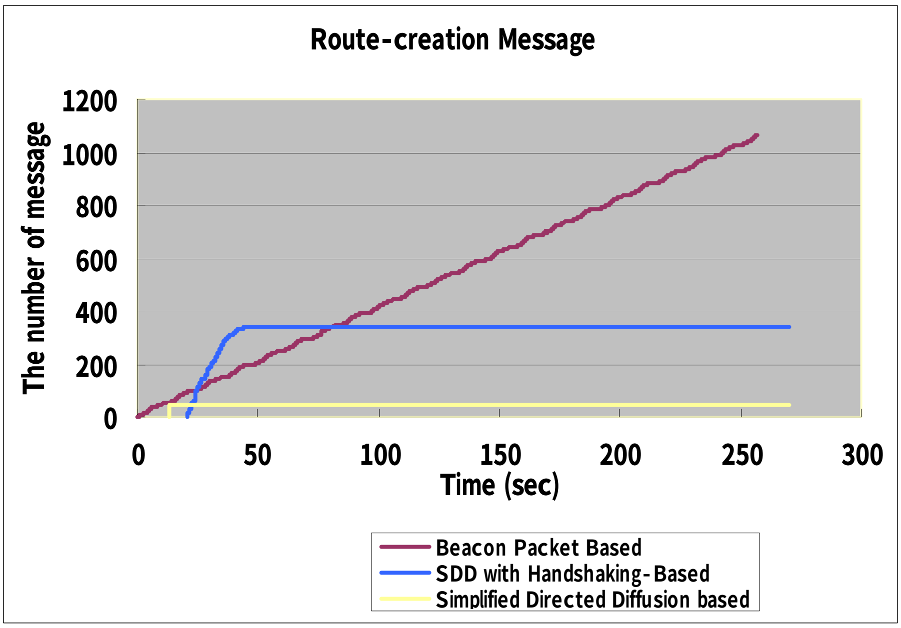


Figure 4.5: Data Transmission in Network Establishment in SDD with Handshaking-based Approach

As can be seen in figure 4.5, the SDD-based approach transmitted more data transmission by the handshaking process. The average total number of *route-creation* message was approximately 340 messages constantly, about 600 percents increasing from the original SDD-based approach. However, by comparing with the BP-based approach, the increment can be considered negligible. During 250 seconds of the evaluation, the SDD-based approach cost 340 messages and this number remains until the network resetting while the BP-based approach transmitted 900 messages and continuously kept sending the *route-creation* message at a constant rate. Since, the operating time extends much longer in a real-world operation; the total number of *route-creation* message becomes larger resulting in a large number of energy wasted from data transmission.

4.3.2 Conclusion and Analysis

The evaluation shows great improvement in term of efficiency in *report* delivery after applying the handshaking to the SSD-based approach. Due to the conclusion in section 3.1 that the BP-based approach is not a appropriate choice because of the high data transmission's problem, the SDD with Handshaking-based approach shows good indications to work instead at nearly the same level of reliability in *report* delivery but cost much less energy from data transmission.

The main factor that makes the quality of communication links better in the SDD with Handshaking-based approach is the condition that a link are promoted only after it has passed the handshaking process. In the original version of SDD-based approach, a sensor node greedily sets the sender of first incoming *route-creation* message to be a parent and the evaluation in section 3.1 has shown that the parent selection was too loosen. Therefore, the handshaking solves the problem by being stricter. A link that can continuously deliver 3 messages without any loss can be considered relatively good and the simulation prove that some bad links were filtered out by this process.

Although the performance of *report* delivery in the SDD with Handshaking-based greatly improved, the quality of information gathering is still not reliable. This evaluation points out a fact that choosing only communication links in good condition is possibly not enough to guarantee the quality of service. This inspires an idea of adding a mechanism that can enhance the quality of data transmission during the operation phase that leads to the proposal of using data retransmission in section 3.3.

4.4 Evaluation of Data Retransmission in Packet Link Layer

An attempt to strengthen communication links proposed in section 3.3 is evaluated by the simulation in this section. Data Retransmission was implemented on top of the SDD with Handshaking-based routing system. The evaluation aims to show the improvement of adding the Packet Link Layer to the networking stack and transmission overhead cost by the retransmission process.

The evaluations are divided into 2 scenarios. In the first scenario, there were 2 sensor nodes in the simulation; one was a sender and another one was a receiver. The sender transmitted 100 messages to the receiver for each simulation and the number of loss message, retransmission message and acknowledgement message in the Packet Link Layer was recorded. There are 2 parameters in this scenario consisting of a distance between those 2 nodes and the Maximum Retransmission (Max RT). The spacing was adjusted between 5-40 feet and the Max RT was switched among 0, 1, 2 and 3. This evaluation aims to show the relationship between those 2 parameters and data loss rate, the number of data transmission and link classification. The simulations were conducted 20 times for each parameter setting.

The second scenario was evaluated through the object monitoring system as similar to the evaluation in both 2 previous sections. 49 sensors were deployed to a rectangular grid with 10 feet spacing and other configuration was set corresponding to the explanation in section 4.1. This evaluation aims to compare the performance of information gathering of a system before and after adding the Data Retransmission. The maximum retransmission was set among 1, 2 and 3 and the simulations were performed 30 times for each setting.

4.4.1 Simulation Result and Analysis of Data Retransmission in Single-hop Communication

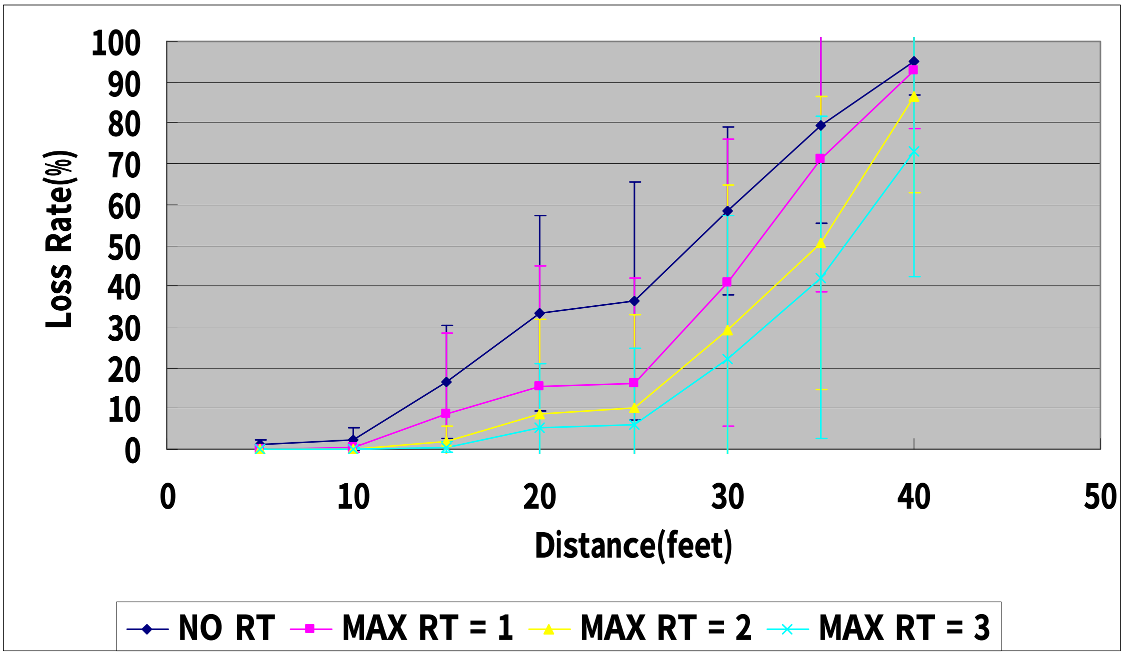
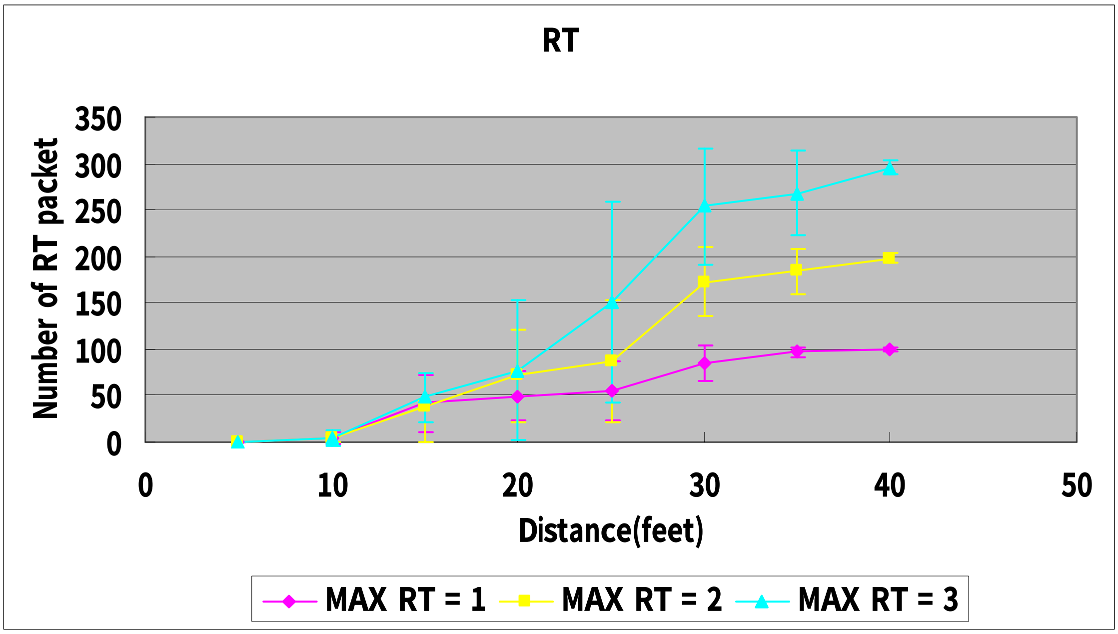


Figure 4.6: Loss Rate in Packet Link Layer in Single-hop Communication

Figure 4.6 shows obviously that Data Retransmission reduced the loss rate of data transmission. Especially, for a distance between 10-25 feet, data transmission without retransmission mechanism had the loss rate up to 35 percents while increased the Max RT to 1, the loss rate fell down more than half. The more the Max RT was increased, the lower the loss rate went down as shown in figure 4.6.

For a distance further than 25 feet, the difference of performance between setting Max RT to 2 and 3 was not significant. This could be implied from the fact that the probability that the condition of links would be very bad was high at this range of distance, therefore, for links that had failed to deliver message for 3 times in a row, they tended to fail the fourth trial.



(a)

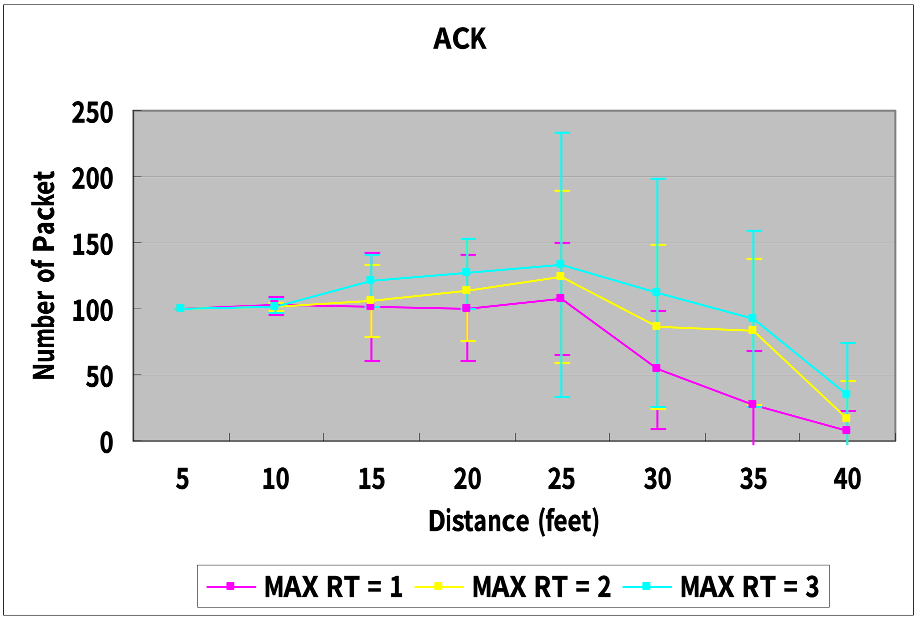


Figure 4.7: Data Transmission in Single-hop Communication
(a) The number of Retransmission (b) The number of Acknowledgement

Data Retransmission mechanism started being executed if the gap was enlarged enough until the data transmission failure occurred. No matter what setting of the Max RT was, the average numbers of data retransmission were nearly the same for a distance shorter than 25 feet. Figure 4.7 (a) shows that the average number of data retransmission less than 100 packets, in other words, less than 1 packet per 1 data transmission because the sender sent 100 messages in one simulation. This implied that only 1 time of data transmission was enough to bring the data to the destination. So, even the Max RT was set to 2 or 3, the second or third retransmission was fairly launched. When a gap became larger, a system with higher setting of Max RT tended to execute more data retransmission. Figure 4.6 has shown that increasing the Max RT could not provide much difference of loss rate. For this reason, setting the Max RT too large can cause a useless waste of data transmission.

Figure 4.7 (b) shows the number of ACK message in the evaluation. The value is nearly constant equals to 100 packets if no packet loss happens. The number of ACK message got larger when the loss of ACK message started happening that forced the sender to retransmit a *RT* message containing the identical payload. The number of ACK message is high in a case that a condition of link in incoming direction for a receiver is very good and a condition in outgoing direction is bad and causes the loss of ACK message. This indicated that the asymmetric phenomenon of communication link was the main cause of the higher number of ACK message. However, since the number of ACK message equals to the number of message which is safely delivered to the receiver, therefore, the number of ACK message gradually decreased when the quality of communication link turned bad.

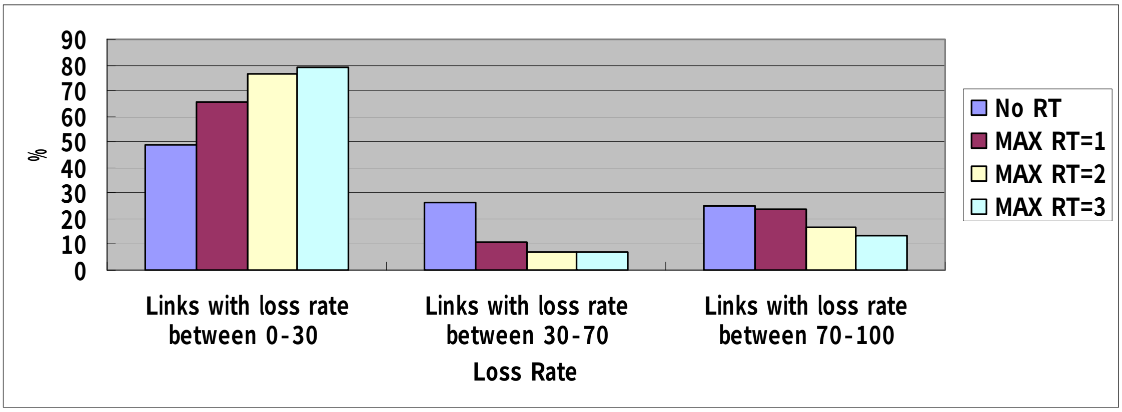
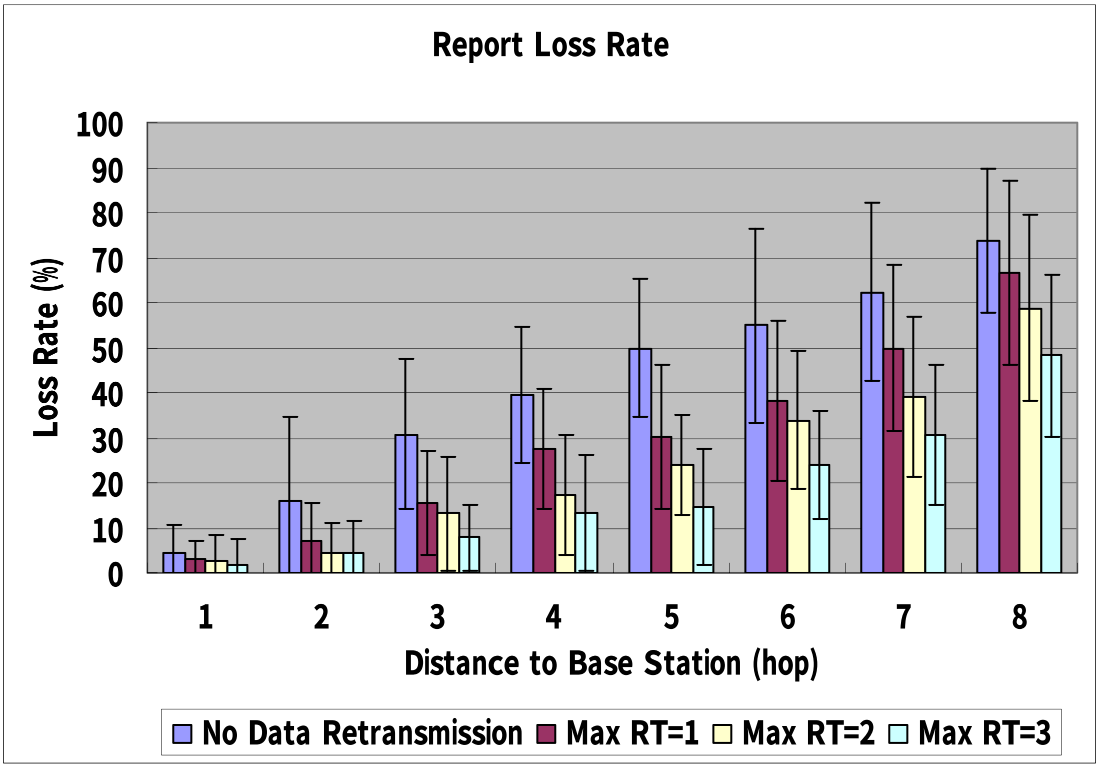


Figure 4.8: Classification of Communication Link by Packet Link Layer

The primary reason of using Data Retransmission mechanism is to solve the loss rate problem. Nevertheless, an application can take indirectly benefit on by-product merit which is the link classification. Figure 4.8 illustrates that higher setting of the Max RT reduces the number of unsteady links. The graph is created by grouping 80 instances of simulation by the loss rate. Unsteady links represent a link whose loss rate is not very good or very bad in one way or another. This kind of link causes the loss rate because a sensor node can not decide whether the link should be removed or not. A mechanism to change the parent node proposed in section 3.4 could take advantage this by-product.

4.4.2 Evaluation of Data Retransmission in Multi-hop Communication



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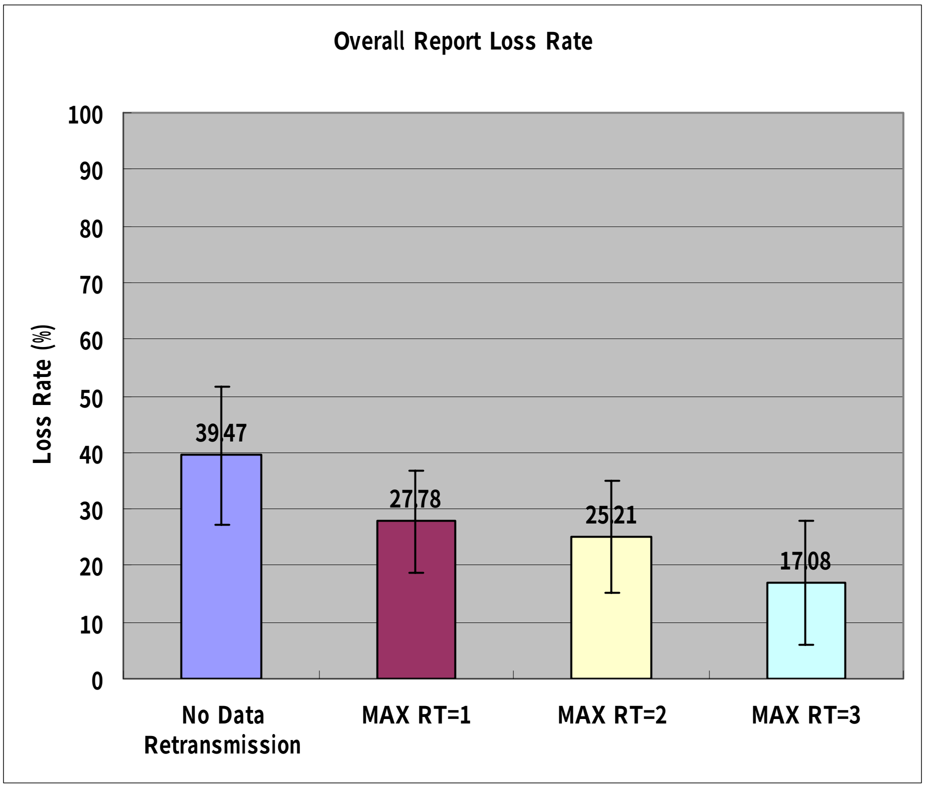


(b)

Figure 4.9: Report Loss Rate in SDD with Handshaking and Data Retransmission-based approach equipped with Data Retransmission:

(a) Report Loss Rate categorized by distance from a sender to the base station

(b) Overall Loss Rate

In this simulation, the Packet Link Layer was implemented and inserted into between Routing layer and Mac layer as explain in section 3.3. The better quality of communication links enabled the *report* delivery to operate at a lower loss rate of *report* as shown in figure 4.9. In addition, the *report* loss rate also varies in proportional to the setting of the Max RT; the larger the Max RT is, the better the quality of communication links are and that directly assists the information gathering.

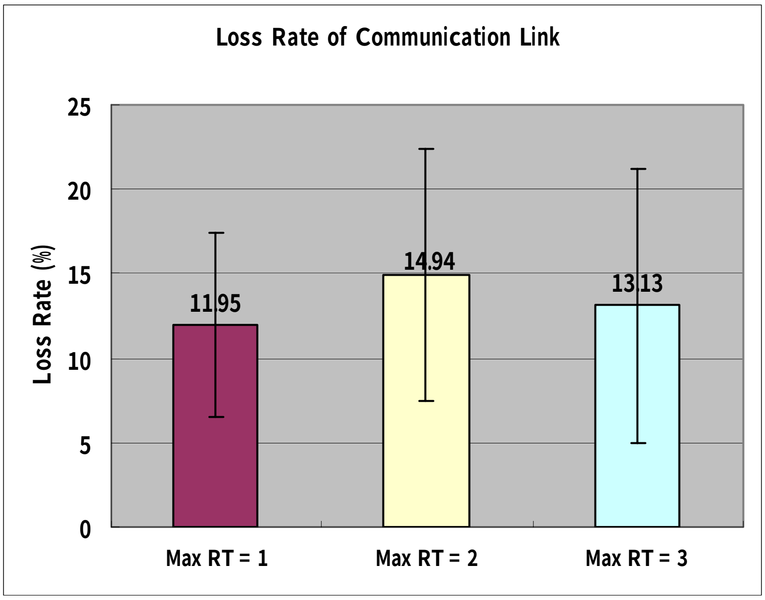


Figure 4.10: Loss Rate of Communication Link in SDD with Handshaking and Data Retransmission-based approach

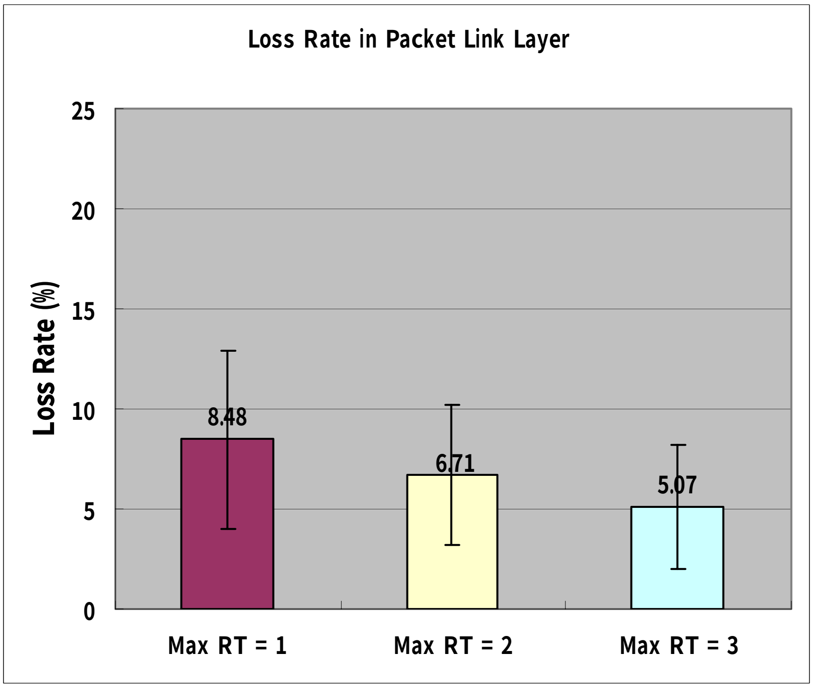
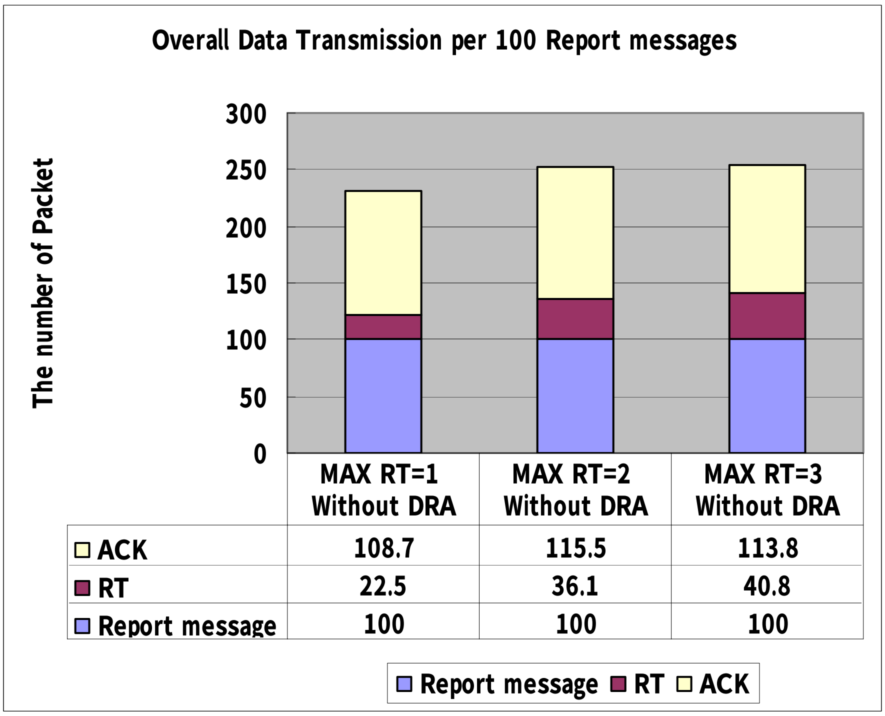


Figure 4.11: Loss Rate in Packet Link Layer of SDD with Handshaking and Data Retransmission-based approach

The SDD with Handshaking and Data Retransmission-based approach does not have a feature to dynamically change the route. Each sensor innocently forwards the data along outputs of the network establishment phase until the timeout of network resetting fires and the *route-creation* message is broadcasted from the base station.

Therefore, this infers that the quality of communication depends merely on the parent selection in the network construction process. However, the result shows that the distribution of link quality is considerably high. Although, the Data Retransmission in Packet Link Layer alleviates the loss rate as can be seen in figure 4.10 and 4.11, the information gathering system still suffers from higher quantity of data transmission in Packet Link Layer to compensate for the transmission loss. Figure 4.11 shows that the loss rate of hop-by-hop communication in Packet Link Layer level diminishes to more than half of the real loss rate of communication links.



	MAX RT=1 Without DRA	MAX RT=2 Without DRA	MAX RT=3 Without DRA
ACK	108.7	115.5	113.8
RT	22.5	36.1	40.8
Report message	100	100	100

Figure 4.12: Overall Data Transmission in Data Retransmission per 100 Report messages

There are 3 types of messages related to this information gathering approach; *report* message, *RT* message and *ACK* message. Each of its definition was described in section 4.2. Firstly, figure 4.12 presents the total number of each types of message. The numbers are all leveled with respect to 100 *report* messages. According to the result, the number *ACK* message is relatively static. As an analysis in section 4.4.1, the acknowledgement does not entirely change in proportional to the Maximum setting. It is only the asymmetric phenomenon of links that causes high transmission of *ACK* message. For this reason, the number of *ACK* message is relatively predictable which is slightly larger than the number of *report* message.

The variable that changes corresponding to the Max RT setting is the number of *RT* message. It is common that the number of data retransmission is inversely proportional to the quality of communication link. If we consider from the average link quality of each evaluations in figure 4.10, the total number of data transmission of the simulation with the Max RT setting to 2 seems to be the largest because of the worst average link quality among 3 evaluations. However, the information gathering with the Max RT setting to 3 produced slightly larger the number of *RT* message. In a case that a truly bad link is coincidentally selected and no any message can be transferred through this link, the Packet Link Layer with the higher Max RT setting always put more effort on sending redundant *RT* message. This kind of link should be a reason why the average number of *RT* message of setting Max RT to 3 was higher despite of the fact that the average quality of communication links was better.

4.4.3 Conclusion and Analysis of Data Retransmission in Multi-hop Communication

The simulation results show that the Data Retransmission in the Packet Link Layer evidently strengthens communication links in the network. The enhancement of foundational infrastructure allows the *report* delivery, in another word, the information gathering to provide more reliability of service; the loss rate of *report* becomes smaller and sensor nodes deployed at further area acquire more opportunity to submit information to the base station. The improvement requires a cost in term of more data transmission. The overhead of Data Retransmission is a function of quality of communication links and the setting of Max RT. In conclusion, the Data Retransmission reduces the *report* loss rate by 56.72 percents when the Max RT is set to 3 and increases more 150 percents of data transmission on link strengthening in a comparison to the approach without the Packet Link Layer implemented.

Both the loss of *report* and a large number of Data Retransmission are caused by the communication links which are not in a good condition. Even the Data Retransmission can reinforce, it can not change the links and this leads to a proposal of Dynamic Route Alteration proposed in section 3.3. The Dynamic Route Alteration takes benefit of the by-product of using the Packet Link Layer that a sensor node can estimate the quality of links from the feedback.

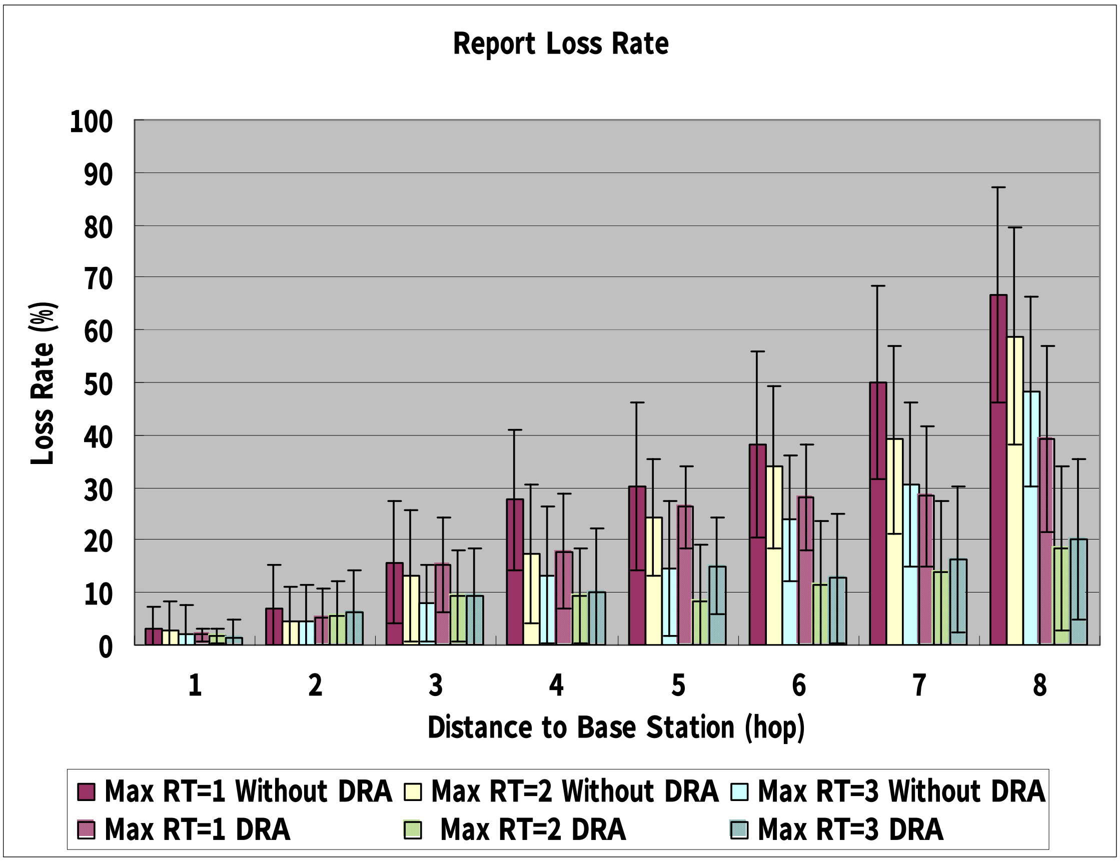
4.5 Evaluation of Dynamic Route Alteration

This section presents the evaluation of the Dynamic Route Alteration which is a mechanism for sensor nodes to dynamically alter the parent nodes in case that the *report* delivery is failed. The DRA explained in section 3.4 was implemented over the SDD with Handshaking and Data Retransmission-based approach. The objective of the evaluation in this section is to show the enhancement of quality of communication links after using the DRA, domino effects to working of Data Retransmission in Packet Link Layer and the overhead caused from the dynamic parent changing.

The conditions of simulation were set corresponding to section 4.1. And this evaluation sets the Max RT as a parameter in the simulation. The Max RT setting involves in 2 significant subjects. First, the larger the Max RT is, the better the quality of hop-by-hop links are that leads to the fewer the DRA will be executed. Second, increasing the value of the Max RT makes the time a sender takes to determine whether the data transmission fails or succeeds becomes longer. Therefore, the extension affects the performance of DRA since the delay of *report* forwarding is a key factor in DRA.

The author divided the simulation scenarios into 3 types. In the first scenario, sensor nodes were deployed as always to a rectangular grid with spacing 10 feet. The second scenario placed sensors to a trigonal grid with spacing 10 feet between each part of adjacent nodes. The objective was to study the performance if the density of neighboring sensor node is larger. And lastly, the sensor nodes were deployed to a rectangular grid with spacing 15 feet in order to represent that the sensor nodes were operating over a worse network. The simulation was conducted 30 times for each setting.

4.5.1 Evaluation on a rectangular grid with spacing 10 feet



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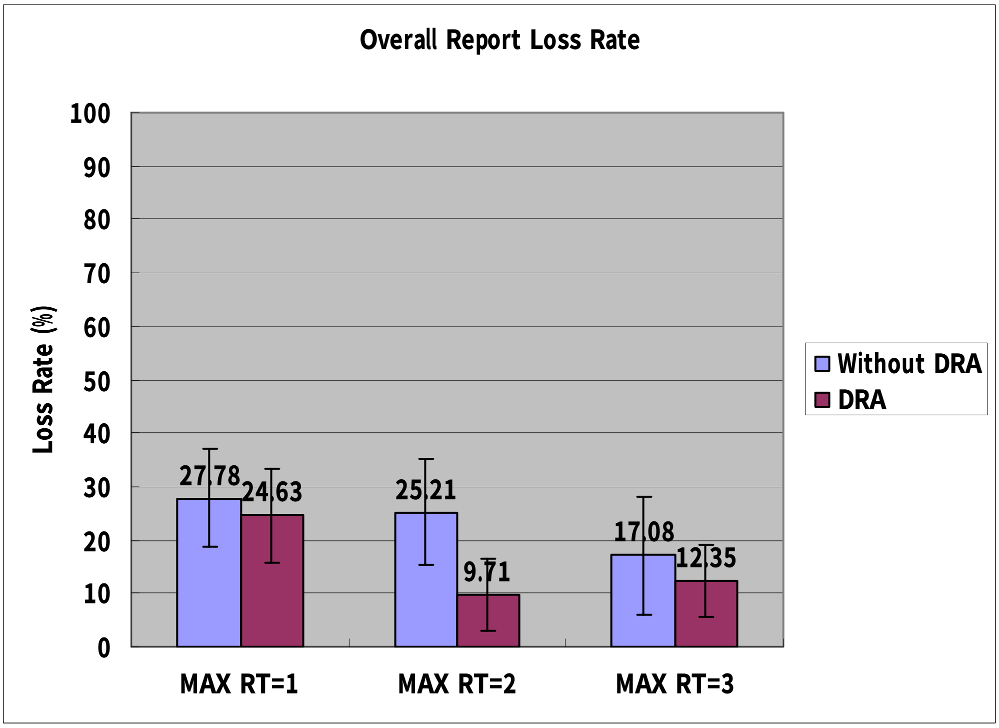


(b)

Figure 4.13: Report Loss Rate of DRA operating over a rectangular grid with 10 feet spacing

(a) Report Loss Rate categorized by distance from a sender to the base station

(b) Overall Loss Rate

Figure 4.13 compares an approach with the DRA and without DRA in term of *report* loss rate. The results unquestionably indicate that the Dynamic Route Alteration allows the object monitoring system to operate over much better elemental communication links. Figure 4.14 shows the evidence of this fact as can be seen that the average loss rate of communication links reduces from 11.95 to 6.6 percents, 14.94 to 5.7 percents and 13.13 to 7.1 percents for a setting of Max RT to 1, 2, and 3, respectively. This means sensor node can change the parent node to a better one which enhances the quality of fundamental communication links. Subsequently, the *report* loss report then decreases in accord. Furthermore, the better communication links makes the loss rate of hop-by-hop communication in Packet Link Layer become smaller as shown in figure 4.15.

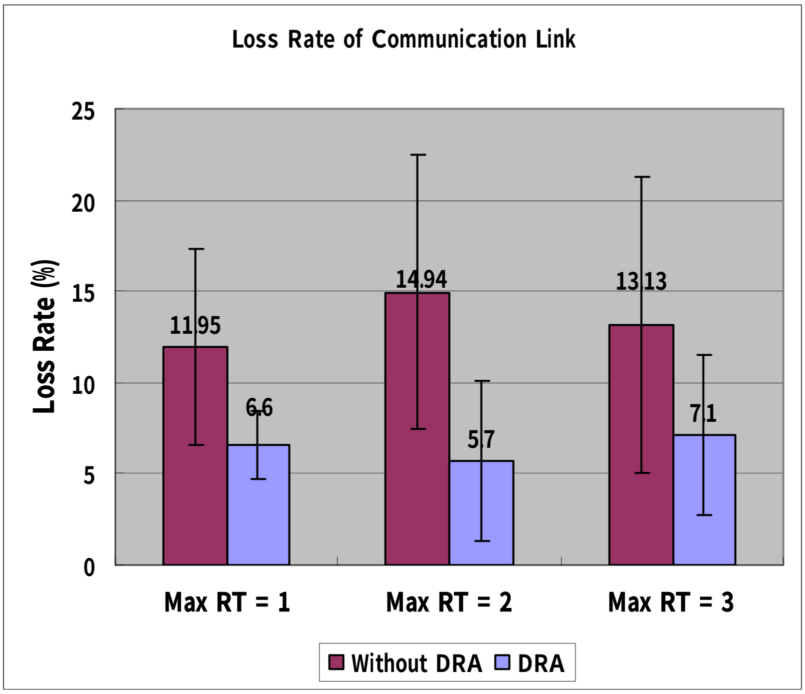


Figure 4.14: Loss Rate of Communication Link in DRA operating over a rectangular grid with 10 feet spacing

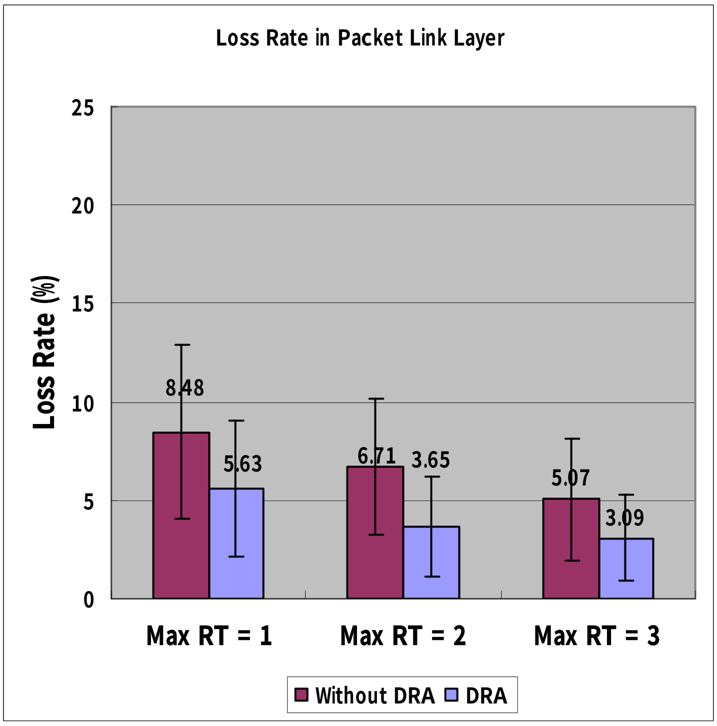


Figure 4.15: Loss Rate in Packet Link Layer of DRA operating over a rectangular grid with 10 feet spacing

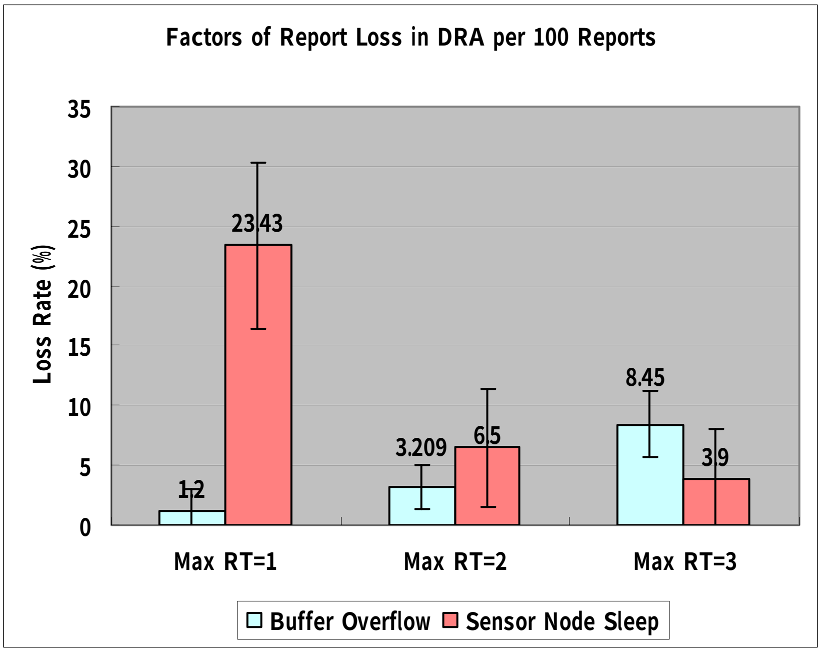
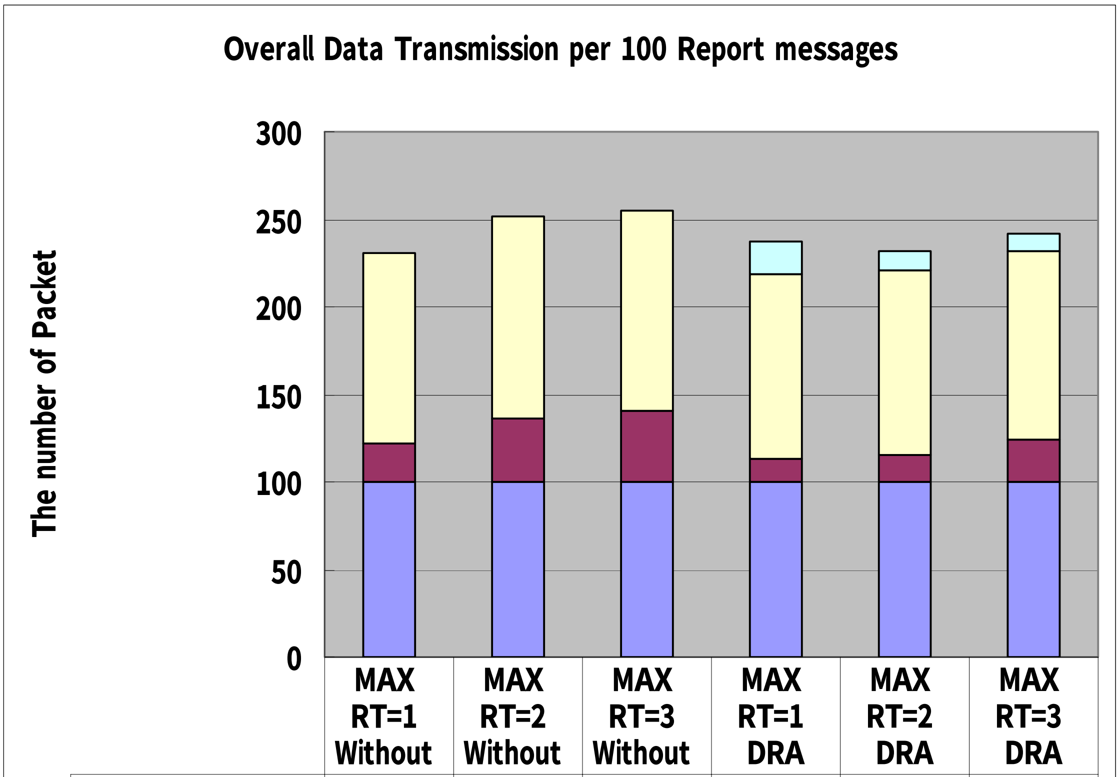


Figure 4.16: Factor of Report Loss per 100 Reports in DRA operating over a rectangular grid with 10 feet spacing

The causes of *report* loss are classified and summarized in figure 4.16. A sensor node shuts down the Packet Link Layer and transits to sleep mode if it has tried requesting all candidates. The loss from sensor node sleep is comparatively high since the strength of hop-by-hop communication is comparatively weak. We can see that the loss gradually decreases in proportional to an increment of Max RT. In contrast, a sensor node with larger setting of the Max RT damages the higher *report* loss which caused by the buffer overflow incident. The buffer overflow happens when an incoming message is transmitted in during the message forwarding or the DRA execution and no space is left in a store buffer, then the incoming message is dropped.

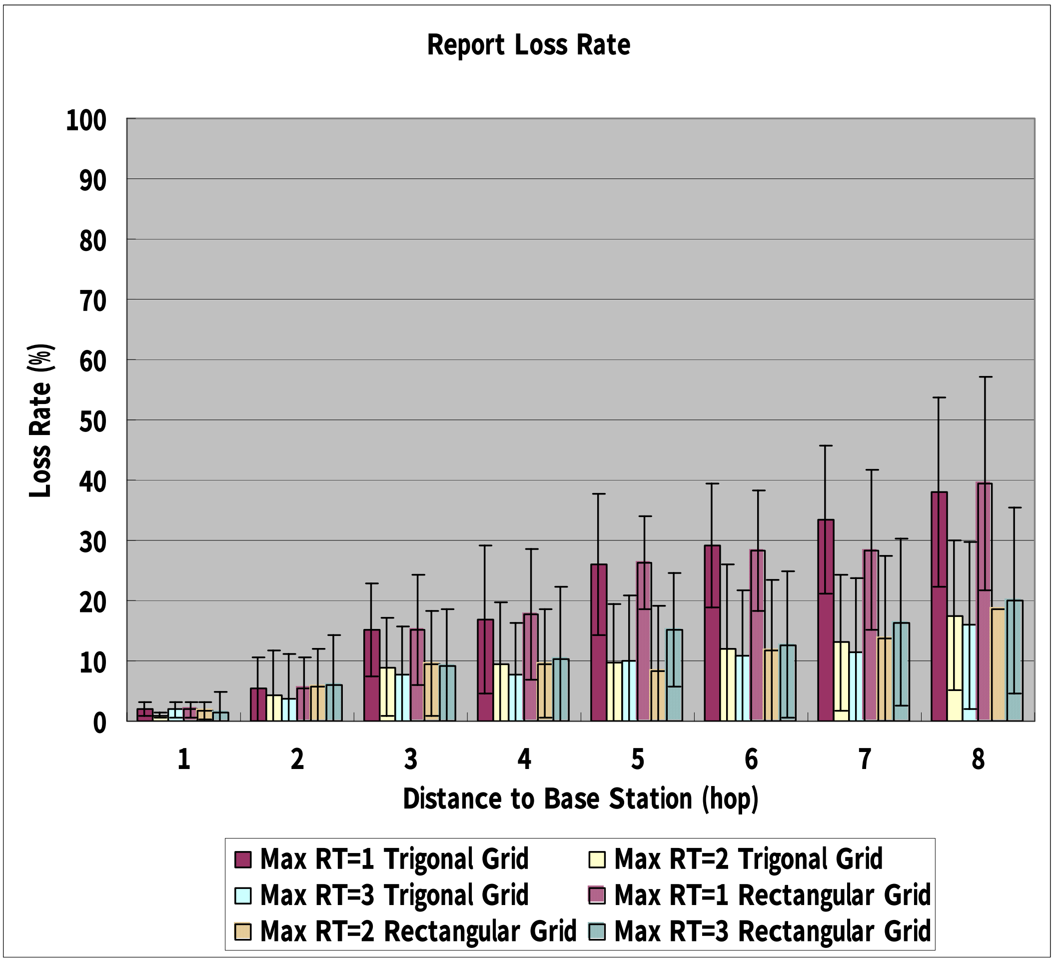


	MAX RT=1 Without	MAX RT=2 Without	MAX RT=3 Without	MAX RT=1 DRA	MAX RT=2 DRA	MAX RT=3 DRA
Dynamic Route Alteration	0	0	0	18.5	10.75	9.53
ACK	108.7	115.5	113.8	106.4	105.5	108.6
RT	22.5	36.1	40.8	12.7	15.5	23.7
Report message	100	100	100	100	100	100

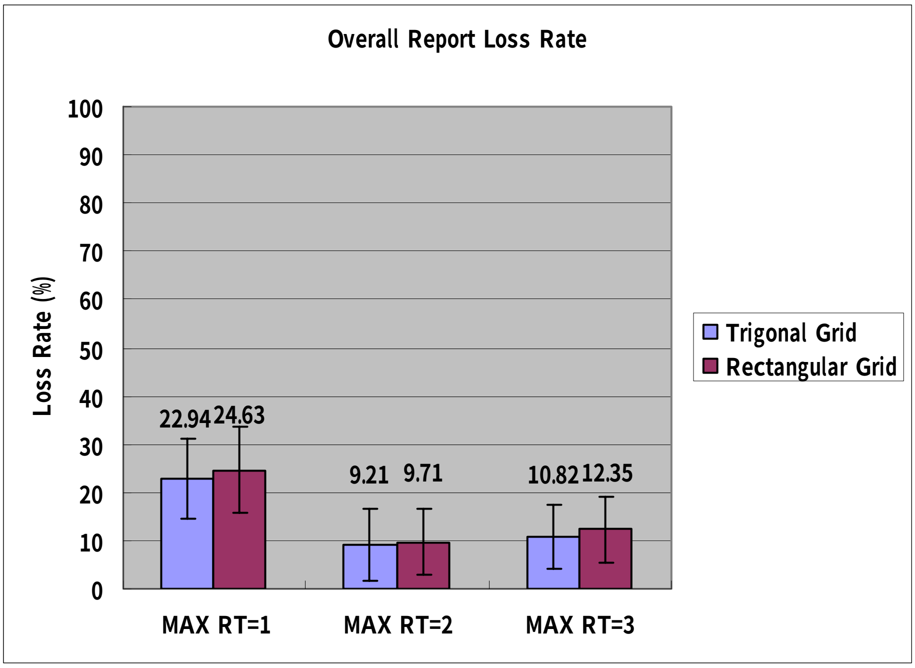
Figure 4.17: Overall Data Transmission per 100 Report messages in DRA operating over a rectangular grid with 10 feet spacing

Since the better communication links were dynamically selected, the number of data retransmission in Packet Link Layer decreased as can be seen in figure 4.17. However, the Dynamic Route Alteration must transmit the request-to-connect message and the acknowledgement, this portion of transmission increases the overall data transmission. Figure 4.17 shows that the total number of data transmission is slightly fewer for an approach with the DRA.

4.5.2 Evaluation on a trigonal grid with spacing 10 feet



(a)



(b)

Figure 4.18: Report Loss Rate of DRA operating over a trigonal grid with 10 feet spacing

(a) Report Loss Rate categorized by distance from a sender to the base station

(b) Overall Loss Rate

This simulation aimed to show the correlation between the density of neighboring sensor node and the performance of DRA. The wireless sensors were deployed in more compact manner to the trigonal grid but the interval distance between adjacent nodes was still equal to 10 feet. This implied that the average quality of communication link was still in the same level but one node tended to be able to connect to the larger number of neighbor. Figure 4.18 shows that the *report* loss rate slightly drops in case of the trigonal grid deployment. The overall loss rate also decreases a bit in all setting of the Max RT.

The quality of fundamental link was on the order of the same level as can be seen in figure 4.19. However, the performance of Packet Link Layer in case of the trigonal deployment improves particularly when the Max RT is set to 2 or 3.

According to figure 4.21, the number of *report* loss caused by buffer-overflow significantly decreases when the Max RT is set to 3. These simulation results show the proof of a fact that the longer time the DRA operation takes, the number of buffer-overflow increases. Due to the larger number of adjacent neighbor, the sensor nodes deployed to the trigonal grid become easier to find candidates, therefore, the time taken by a candidate searching and negotiation becomes smaller and further reduces the probability of the occurrence of buffer-overflow. For the *report* loss caused by the sensor node sleep' side, the simulation with a setting of the Max RT to 1 produced less the loss rate. The object monitoring system with a setting of the Max RT to 1 operates over the weakest hop-by-hop communication links comparing to other settings; the sensor nodes more frequently fail to forward *reports* which makes the sensors transit to the sleep mode by the DRA mechanism more often. The larger density of neighboring node allows the sensor nodes to gain more opportunity to find other candidates of being a parent that prolongs the operation without sleeping.

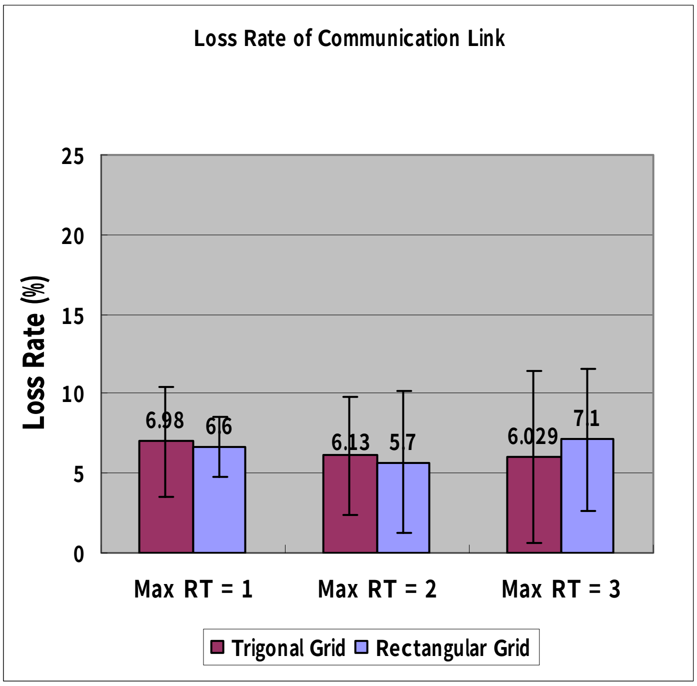


Figure 4.19: Loss Rate of Communication Link in DRA operating over a trigonal grid with 10 feet spacing

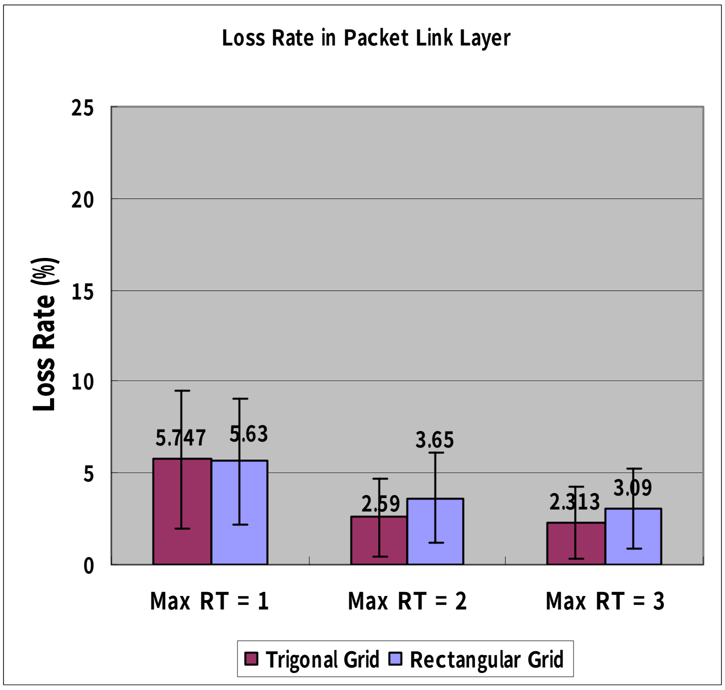


Figure 4.20: Loss Rate in Packet Link Layer of DRA operating over a trigonal grid with 10 feet spacing

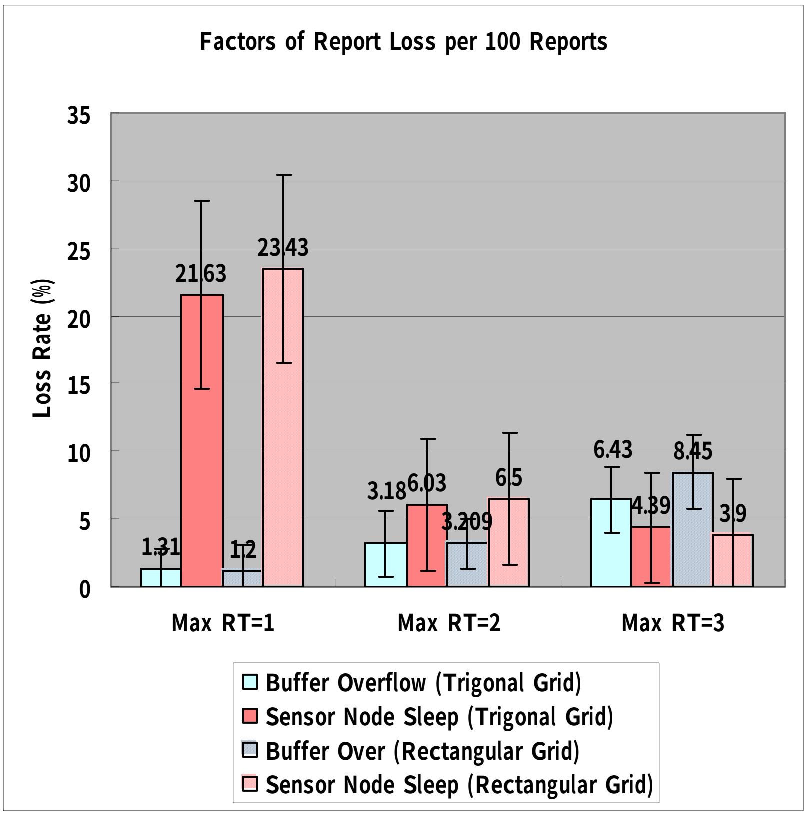
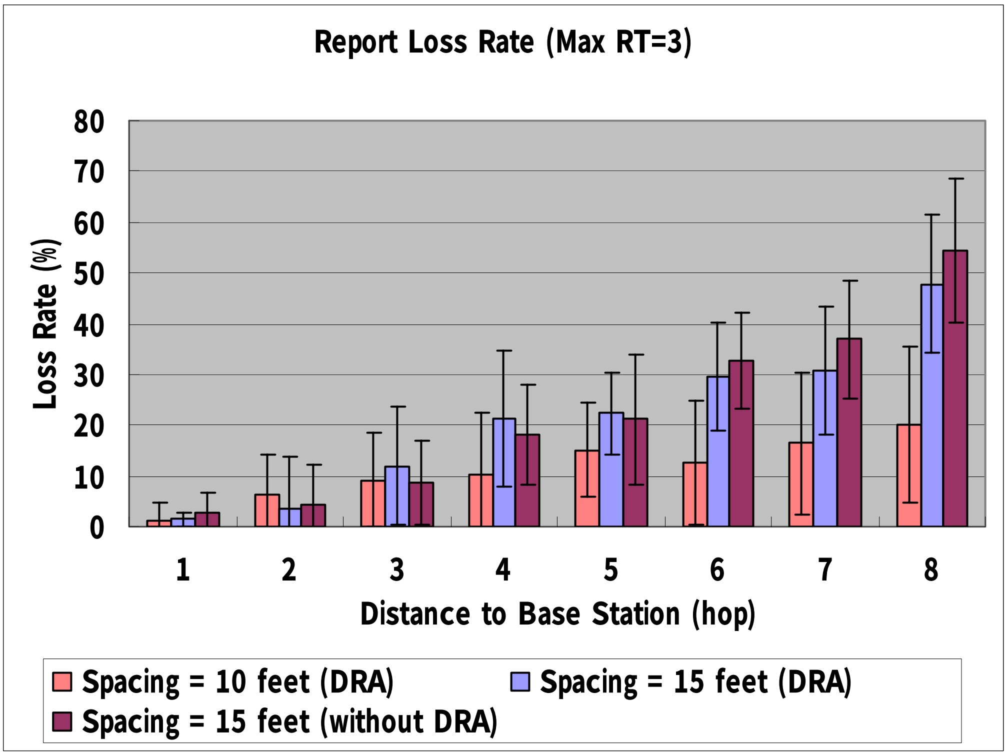
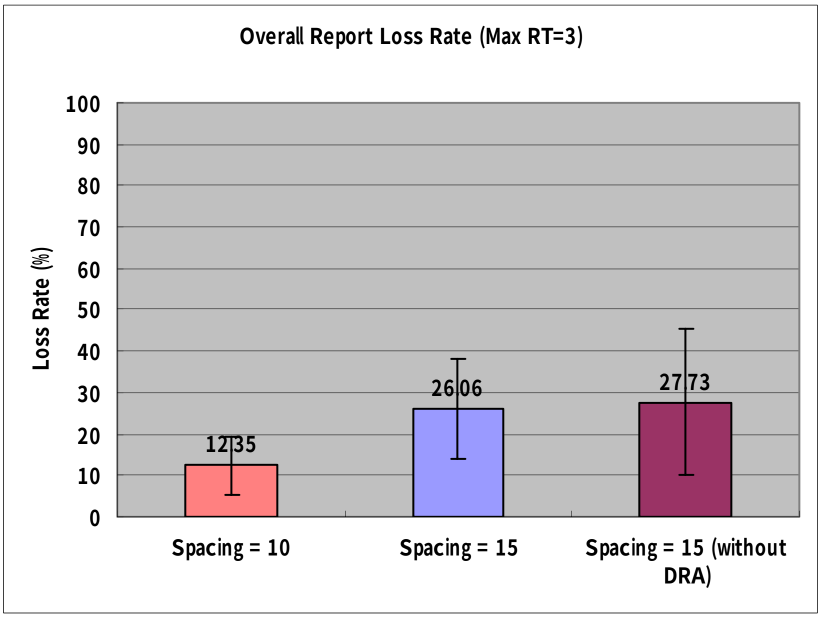


Figure 4.21: Factor of Report Loss per 100 Reports in DRA operating over a trigonal grid with 10 feet spacing

4.5.3 Evaluation on a rectangular grid with spacing 15 feet



(a)



(b)

Figure 4.22: Report Loss Rate of DRA operating

over a rectangular grid with 15 feet spacing

(a) Report Loss Rate categorized by distance from a sender to the base station

(b) Overall Loss Rate

The objective of this simulation is to study the performance of the Dynamic Route Alteration while operating over the network of more separated wireless sensors. The wireless sensors were deployed to a rectangular grid with spacing 15 feet. Hence, even the most adjacent pairs of nodes, the quality of link tends to be unsteady. As shown in figure 4.22, the *report* loss rate increases in proportional to the distance interval. An approach without the DRA mechanism was also evaluated and compared with the case of using DRA. According to the simulation results, the DRA assists in the enhancement of *report* delivery and the improvement of fundamental communication link as can be seen in figure 4.23 and 4.24, however, not as much as in a case of operating over more compacted network such as in a case of a grid network with spacing 10 feet.

Due to the worse quality of network, the probability of Data Retransmission failure in the Packet Link Layer increases which leads to the higher *report* loss rate caused by the sensor node sleep as can be seen in figure 4.25. Furthermore, dwindling density of sensor nodes obstructs the new parent searching process which further results in a longer delay of DRA execution and subsequently increases an occurrence of the buffer-overflow.

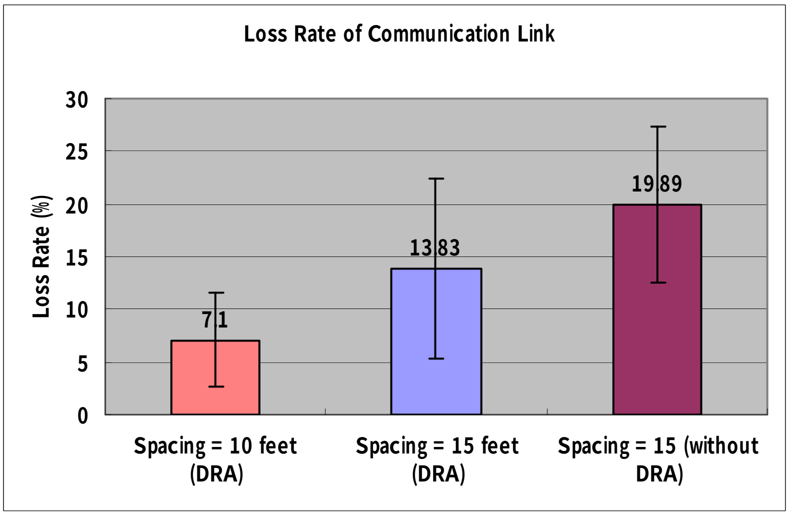


Figure 4.23: Loss Rate of Communication Link in DRA operating over a rectangular grid with 15 feet spacing

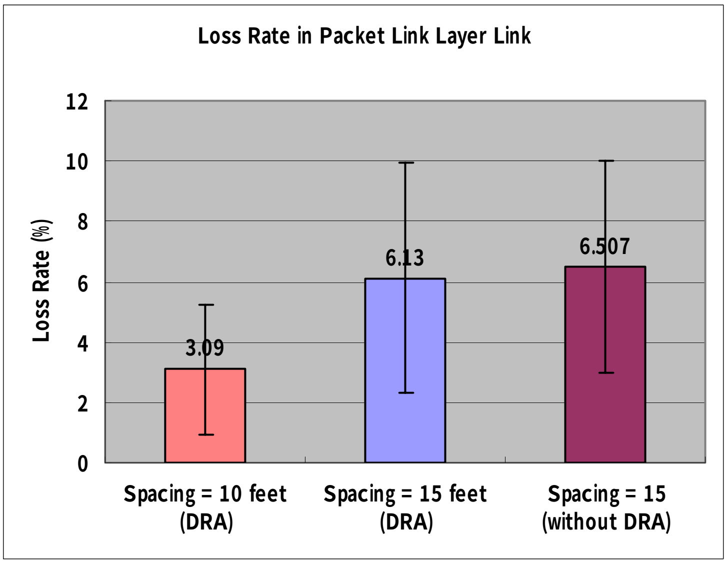


Figure 4.24: Loss Rate in Packet Link Layer of DRA operating over a rectangular grid with 15 feet spacing

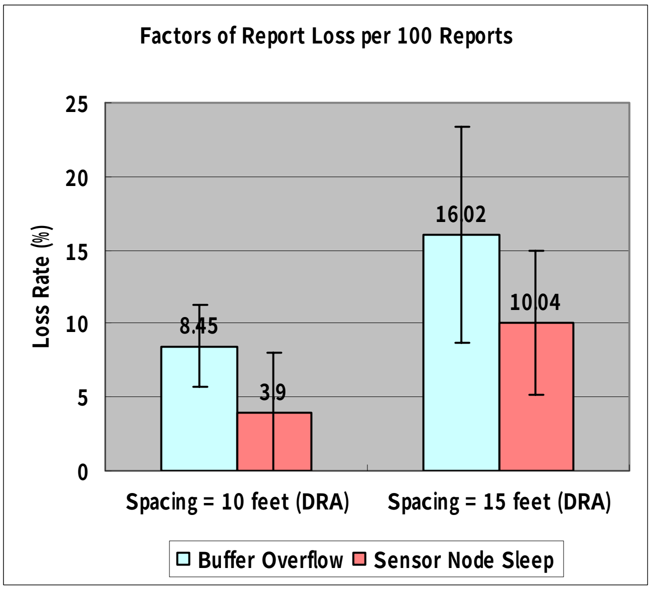


Figure 4.25: Factor of Report Loss per 100 Reports in DRA operating over a rectangular grid with 15 feet spacing

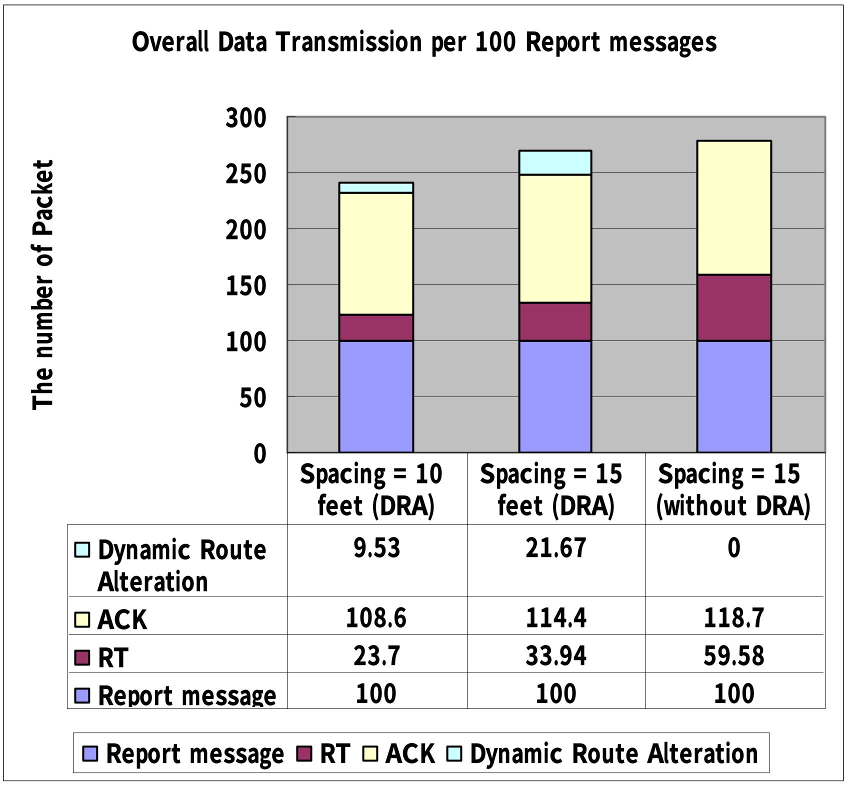


Figure 4.26: Overall Data Transmission per 100 Report messages in DRA operating over a rectangular grid with 15 feet spacing

In figure 4.26, the total number of data transmission in a case of spacing 15 feet is larger than the same number in a case of spacing 10 feet. The worse average loss rate of fundamental links enforces the Packet Link Layer to transmit more *RT* message. Moreover, the success rate of the request-to-connect process in DRA also decreases so the number of parent negotiation becomes larger. However, the DRA can reduce the number of *RT* message by improving the routing path.

4.5.4 Conclusion and Analysis

The simulation results show that the Dynamic Route Alteration enhances the quality of fundamental links during the operation phase. Unlike the Data Retransmission in section 4.4, the DRA changes communication links rather than strengthening the current infrastructures. The combination of both two mechanisms can collaboratively work together and levels up the reliability of information gathering as shown in section 4.5.1.

The DRA operation demands the transmission overhead compensated for the improvement of link quality but the enhanced infrastructure afterward reduces the data retransmission. Therefore, the DRA slightly reduces the total number of data transmission in conclusion.

As the design of DRA which is over an assumption that there exists at least one way to forward the message in low-loss rate manner, sensor node put the best effort to deliver *report* message. For this reason, the benefit of using DRA can not be efficiently taken when operating over a bad infrastructure as shown in section 4.5.3. The simulation in section 4.5.2 additionally affirms that the DRA shows the best productivity if operating over high-densely deployment of wireless sensors.

4.6 Discussion

The proposals are evaluated through the simulations and the results are discussed in previous sections. Lastly, the parameter configuration is discussed in this section to shows how to set each parameter when this information gathering system is used in other applications of wireless sensor networks.

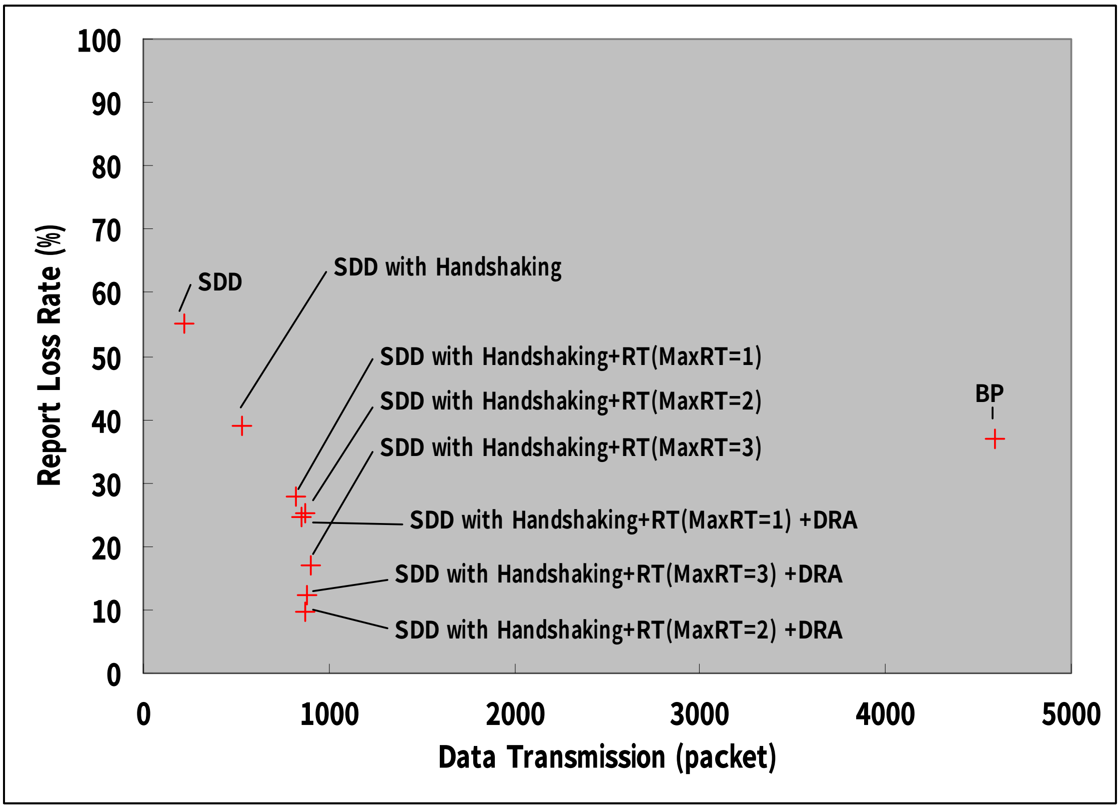


Figure 4.27: Conclusion of Report Loss Rate and Data Transmission in Each Design of Information Gathering System

The author has concluded the evaluation results of each design and configuration at figure 4.27. Figure 4.27 depicts the *report* loss rate and total number of data transmission for each design of the object monitoring system which operated for 1000 seconds. During operating, the measurement was conducted under the assumption that there was an object moving in the operation area for 200 seconds. This means the sensor nodes had spent 800 seconds or 80 percents of time on idle state waiting for incoming objects. The simulation was done over the network of 49 sensor nodes deployed into a grid of 7x7 with spacing 10 feet and a sensor node each inspects an object every 5 seconds.

As can be seen in figure 4.26, the SDD with Handshaking and Data Retransmission and Dynamic Route Alteration-based approach when the Max RT is set to 2 outperforms the other approaches in term of reliability. And even though the total number of data transmission is more than some other approaches such as an approach without the DRA and the Max RT is set to 1 or 2, only the very tiny increment of data transmission is unquestionably worth for reducing the *report* loss rate from approximately 25-30 percents to 10 percents. The approach with a setting of the Max RT to 2 also shows better performance then others with a setting of the Max RT to 1 or 3 by the reasons described in section 4.6. For this reason, the author concludes that the SDD with Handshaking-based approach which is equipped with the DRA mechanism the Packet Link Layer for the Data Retransmission and is set the Max RT to 2 is optimal to be used as the information gathering module in applications operating over densely deployed wireless sensors.

This research considers the reliability of information gathering and energy efficiency as the primary attributes and leaves other typically important attributes including latency, throughput and bandwidth utilization to be secondary. However, the Max RT setting highly influences upon the maximum throughput and if the demanded rate of data transfer exceeds the maximum throughput, the loss of *report* message happens as well. Therefore, the author discusses in brief the relation between parameters setting of the proposals and the maximum throughput of information gathering.

Since the total time for a sensor node to determine whether the data transmission fails or not is directly proportional to the value of the Max RT; the larger the Max RT is, the longer the maximum delay is. Therefore, setting the Max RT too large reduces the maximum throughput of the communication protocol that leads to another cause of message loss when the *report* delivery module can not provide enough rate of transfer required by applications.

The evaluation of DRA in section 4.6 shows a good example of such a *report* loss case when the Max RT equals to 3. Increasing the Max RT from 2 to 3 decreased the maximum throughput to below the demand in some period of operating time leading to the buffer-overflow. In order to enlarge the maximum throughput, the author introduces 3 solutions as follows.

1. ***Reducing the round-trip time in the Mac layer***

   It further decreases the length of timeout in the Data Retransmission process. Therefore, a sensor node can recognize within smaller delay that the data transmission fails. In the simulation over TOSSIM, the author could not assume the round-trip time in Mac layer less than 500 milliseconds which, in a real-word wireless sensor, should be much smaller. This compels the Packet Link Layer to wait at least 500 milliseconds in the simulation to determine whether the acknowledgement is replied back or not and results in a very long delay caused by the data retransmission process and finally presses the maximum throughput of information gathering down to unbelievably low. If the information gathering module proposed in this research is used in the real-world application, the first task users need to do is adjusting the length of timeout in Packet Link Layer to be corresponding to the actual round-trip-time over the Mac layer. For example, if the acknowledgement is sent back within 50 milliseconds since the data is sent out, the appropriate timeout in the Packet Link Layer is 50 milliseconds.

2. ***Increasing the size of message buffer in the Routing Layer***

   The bigger size of message buffer enables an intermediate node located along the routing path to store more *report* message during waiting for the DRA. In size of message buffer in the simulation was set to 10 messages; 2 times of the maximum number of *report* message that can be transmitted to the same node at the same moment. This value is calculated from the conditions that the sensing range is 10 feet and the rectangular-grid deployment with spacing 10 feet of sensor nodes bounds the number of sensor that can simultaneously detect the object to 5 nodes. However, it does not mean that the message recovered from being dropped by increasing the size of buffer will be all delivered to the destination. The circumstance which there is a large number of messages in the buffer can be indirectly implied that the sensor node is in trouble and looking for new parent. So, all rescued message might be removed if the sensor fails in finding the parent. Furthermore, in an application which the memory constraint of wireless sensor is significant, excessively increasing the size of buffer should be avoided since it does not direct help the performance of information gathering.

3. *Decreasing the Max RT*

The main reason why the author suggested setting the Max RT is that increasing the Max RT from 2 to 3 did not show meaningful change of reliability of *report* message. On the one hand, increasing the Max RT reduces the loss of message by strengthening the communication link; on the other hand, it enlarges the delay which reduces the maximum throughput as mentioned and finally causes the loss of message. Furthermore, since the increment of the Max RT when its value is basically high does not enhance the improvement of fundamental links, it is more secure not to set the value of Max RT too high and 2 is proved by the evaluation the proper value. The Max RT is an important attribute related to trade-off among throughput, latency and reliability of service.

Lastly, the author concludes the way of deployment as follows. Firstly, the wireless sensors must be densely deployed so that the proposed mechanisms can operate in the good efficiency according to the simulation results. The density of sensor deployment is up to the radio communication range. The information gathering module provides high performance if sensor nodes have enough number of neighbors within a range whose loss rate is lower than 10 percents in average. According to the evaluation which there was 4 nodes within the reliable communication range, the performance of *report* delivery was satisfied. In addition, increasing the density of sensor node inside the reliable communication range further enhances the efficiency as presented in the evaluation over a trigonal grid of wireless sensors.

Chapter 5

Conclusion

5.1 Conclusion

Information gathering is one of the common but indispensable operations used in several applications of WSNs. From the evaluations and reports of other researches, the current widely used approaches, including the Beacon Packet-based routing system (BP) and the Simplified Directed Diffusion-based routing system (SDD), have some problems in packet loss and high data transmission.

Since the SDD-based approach conserves the energy consumption in the network establishment phase, the author decided to inherit the technique in developing the information gathering module. However, due to the fact that the SDD-based approach completely fails the requirement in term of reliable information delivery, the author introduced 3 additional mechanisms to enhance the reliability of information gathering under the consideration of energy consumption caused by data transmission.

The author firstly proposed applying the well-known Handshaking to the network establishment phase in order to enhance the quality of fundamental communication links. The problem found in the evaluation was the SDD-based approach used a loose method to select the communication link. Hence, the Handshaking makes the selection process become stricter which results in the better average quality of output of selection process.

In the operation phase, the author introduced 2 mechanisms to reduce the loss of message. The Packet Link Layer was placed between the Routing Layer and Data Link Layer in networking stack to control the Data Retransmission process. The Data Retransmission leveled up the infrastructure in a defensive manner; it strengthened the communication links by retransmitting identical messages after transmission failure at below layer. The evaluation showed great reduction of loss rate by using the Data Retransmission.

Another mechanism to reduce the loss of information is the Dynamic Route Alteration (DRA). Instead of solving in a defensive manner as the Data Retransmission, the DRA changes the routing path in case that the links are out of hand to be used even strengthened by the Data Retransmission. This allows the network to adapt to better structure during operating and the evaluation showed great improvement both in term of more reliable report delivery and indirectly reducing the number of data retransmission in the Packet Link Layer.

The performance evaluation of 3 proposed mechanisms was conducted over TOSSIM, a simulator of TinyOS. According to the simulation results, the combination of those 3 mechanisms outperformed the previous approaches in term of message loss rate and transmission overhead. At the conclusion of the evaluation, the author presented a discussion on parameters configuration to accommodate for putting the proposed information gathering system into practice.

List of Publications

[1] **W. Apirakviriya**, H. Aida, “A Communication Protocol for Information Gathering over Wireless Sensor Network”, The 6th Forum on Information Technology (FIT2007), September 2007.

[2] **W. Apirakviriya**, H. Aida, “A Communication Protocol for Information Gathering over Wireless Sensor Network”, IEICE General Conference, March 2008. (To be presented)

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