國立臺灣大學資訊管理學研究所碩士論文

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具資料集縮能力無線感測網路
系統生命週期之最大化

Maximization of System Lifetime for Data-Centric Wireless Sensor Networks

研究生： 郭文政 撰

中華民國九十五年七月


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本論文係提交國立臺灣大學
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學位所需條件之一部份

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謝　詞

本論文的完成，象徵人生求學生涯的一個階段，也開啟了人生的另一旅程。謹以此論文獻給我的父親郭華富先生與我的母親陳雲娥女士，感謝您們在我求學生涯中全力地支持與鼓勵，使我得以在今日完成碩士學位論文。

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于臺大資訊管理研究所

民國九十五年八月

論文摘要

論文題目：具集縮能力無線感測網路系統生命週期之最大化

作　　者：郭文政

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近年來，無線感測網路在於諸多應用上都具有其優越性。然而，在硬體和環境的限制下，感測器對於能源消耗具有高度限制性。採用資料集縮(data aggregation)能夠有效率地降低資料傳送量，以達到節省能耗的目的。

本篇論文研究在感測器具有資料集縮能力之無線感測網路中，使用集縮樹的適當路由分配以完成最大化系統生命週期。我們將問題化為一個數學模式，目的函式為最大化系統生命週期，並採用拉格蘭日鬆馳法獲得近似最佳解。

關鍵字：生命週期、資料集縮、高效率節能、資料中心路由、最佳化、拉格蘭日鬆弛法、整數線性規劃、無線感測網路。

THESIS ABSTRACT

GRADUATE INSTITUTE OF INFORMATION MANAGEMENT

NATIONAL TAIWAN UNIVERSITY

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MAXIMIZATION OF SYSTEM LIFETIME FOR DATA-CENTRIC WIRELESS SENSOR NETWORKS

In recent years, wireless sensor networks have the advantages in a variety of applications. However, due to the limitations of hardware and the environment, the sensors are highly energy-constrained. By adopting data aggregation, we can effectively reduce the amount of data and thereby save energy consumption.

In this thesis, we adopt data aggregation trees to efficiently arrange routing assignments in order to maximize the system lifetime of data-centric WSNs. We model the problem a mathematical formulation, where the objective function is to maximize the system lifetime, and use Lagrangean Relaxation method to derive an optimal solution.

Keywords: Lifetime, Data aggregation, Energy-Efficient, Data-centric Routing, Optimization, Lagrangean Relaxation Method, Integer Linear Programming, Wireless Sensor Network.

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Chapter 1 Introduction

1.1 Background

In recent years, wireless sensor networks (WSNs) have attracted a great deal of attention. WSN consists of small, inexpensive sensors capable of sensing environmental information, such as temperature, humidity, and ocean currents, and then reporting the sensed data. Each sensor in WSN transmits sensed data to a sink node or base station through wireless communication. There are a variety of applications of WSNs, especially in environments that are difficult to access. For example, sensors can be deployed in the battlefield to monitor an enemy's activities. We can also scatter sensors over the ocean to observe variations in ocean currents, and arrange sensors in a seismic belt to detect earthquakes.

Several factors should be taken into account when designing the WSNs, such as coverage, end-to-end delay, and lifetime. The battery capacity level of sensors is fixed and it is infeasible to recharge the batteries, so the power is consumed rapidly by operations. Therefore, how to prolong system lifetime of WSNs is a fundamental issue.

As shown in Figure 1-1, the sensor nodes are usually scattered in a sensor field. As an event occurs, such the temperature rising above a predefined threshold, sensor nodes within a specific sensing range sense the event and collect the data, and then transmit it to the sink node or base station for further processing. The sink node is depicted as *data sink* and each sensor node within the sensing range is depicted as *data source* node since data is produced by these sensors. The scenario described above is called *event-driven* because the sensor nodes are designated to monitor some events of interesting. There are two other applications of WSNs, called *periodic* and *query-based* WSNs. In the former, all data source nodes periodically sense the events and report the sensed data to the sink node; in the latter, users can request information from some sensor nodes any time.

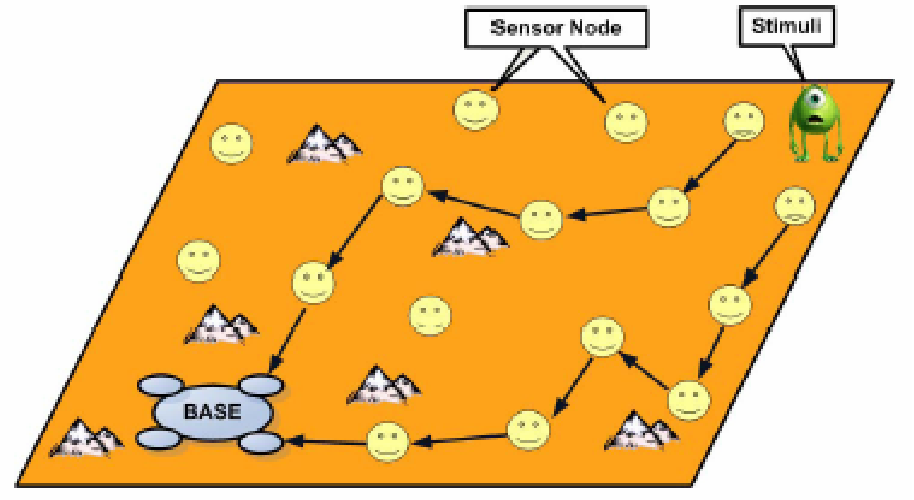


Figure 1-1. A typical wireless sensor network

In both event-driven and periodic models, when a specific event occurs, the raw data is collected and processed before relaying it to the sink node. During the processing, duplicate and useless data is abandoned. The data source nodes are responsible for collecting the raw data, and the intermediate nodes are responsible for aggregating and transmitting it to the sink node through a *reverse multicast tree* where multiple data source nodes transmit information to the sink node. This process is called *data-centric routing*.

Data aggregation is the key to data-centric routing. By aggregating the data from different source nodes, duplicate information can be eliminated; thus, the total number of transmissions can be reduced. By adopting data aggregation, we can achieve energy-efficient transmission.

1.2 Motivation

The construction of a data aggregation tree in which multiple sensor nodes sense data and transmit the sensed data to the sink node is a complicated problem to solve. The aggregation trees we adopt in WSNs significantly affect the power consumption of sensor nodes and further affect the system lifetime.

Therefore, a meaningful mathematical formulation of wireless sensor networks is essential. Through the mathematical model, we can understand the theoretical bounds of the performance, and the impact of different input parameters such as the number of nodes, topology, battery capacity level, etc [1].

In this paper, we take an optimization based modeling approach. We propose a linear integer programming problem to construct a network topology and arrange the routing assignments in WSNs. In this model, we take data aggregation and battery capacity constraints into consideration and the objective function is to maximize the sensor network system lifetime. We then use Lagrangean Relaxation method to near optimally solve this problem.

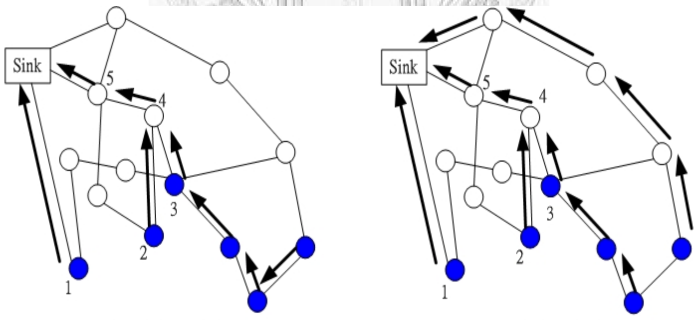
1.3 Literature Survey

In this section, we survey the design problem of WSNs with data aggregation properties and the algorithms for prolonging system lifetime.

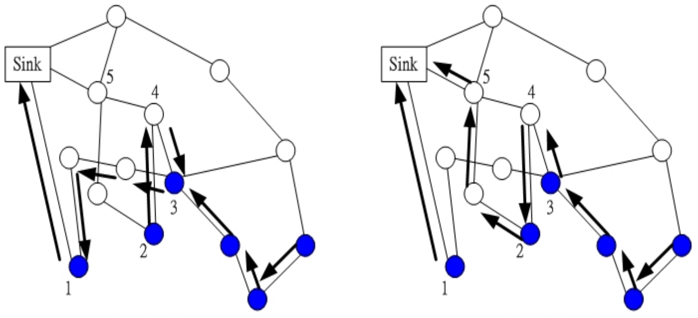
1.3.1 Data Aggregation Tree

Power consumption has a great impact on the system lifetime of WSNs. Therefore, many researchers focus on designing routing algorithms to reduce power consumption and prolong system lifetime. In [2][3][13], the authors discuss the periodic wireless sensor networks where the sensor nodes transmit one data unit of traffic through the aggregation tree to the sink node in a round. The data source nodes construct aggregation trees to send the sensed data to the sink node in each round in order to maximize the total number of rounds. In [2], linear programming is used to solve the problem, and [3] adopts Prim’s algorithm to get a minimum cost spanning tree as the data aggregation tree to transmit sensed data to the sink node. After a predefined number of rounds, the source nodes reconstruct the minimum cost spanning tree as the data aggregation tree. When we construct the data aggregation tree, the weight is the remaining battery power of sensor nodes. The more there is, the grater probability that the sensor will be selected as an intermediate node. By adopting the remaining battery power concept, the sensitivity of sensor nodes to the spanning tree is improved. In [13], the authors proposed a chain-based protocol, namely Power-Efficient Gathering in Sensor Information System (PEGASIS), in order to extend system lifetime. This algorithm constructs a chain to transmit information by greedy method.

In [4], three suboptimal heuristics are proposed for constructing the data aggregation trees, namely, Shortest Path Tree (SPT), Centre at Nearest Source (CNS), and Greedy Incremental Tree (GIT). Figure 1-2 is a simple illustration of these three heuristics. Note that the transmission cost on each link is set to 1. In the SPT data aggregation scheme, each data source node has to construct the shortest path to the sink node and send the sensed data through that path. If the paths of different source nodes overlap, they are combined to form an aggregation tree. Figure 1-2 (b) shows that the aggregation constructed by SPT scheme is not the optimal solution. In CNS data aggregation scheme, all data source nodes send their data directly to the node nearest to the sink node, and it sends the aggregated information to the sink node. Figure 1-2 (c) shows that the aggregation tree built by adopting CNS heuristic. In this case, nodes 2 and 3 transmit data via aggregation node 1, rather than directly transmitting it to the sink node. Thus, it does not achieve the optimal solution, either.



(a) Optimal Cost = 8. (b) SPT Cost = 11.



(c) CNS Cost = 9. (d) GIT Cost = 9.

Figure 1-2. A simple illustration of SPT, CNS, and GIT

In the GIT scheme, the aggregation tree is constructed step by step. In the first step, the aggregation tree is only a sink node. Then, the source node closest to the current tree is joined to that tree until all data source nodes are included in the tree. GIT scheme shown in Figure 1-2 (d) is obviously not an optimal solution, since node 2 does not select the path through nodes 4 and 5 to reach the sink node.

1.3.2 Clustering

In [11], the authors introduced a cluster-based algorithm for sensor networks, called Low Energy Adaptive Clustering Hierarchy (LEACH). The operation of LEACH is separated into two phases, the setup phase and the steady state phase. In the setup phase, each sensor selects a random number between 0 and 1. If this random number is less than the threshold of T(n), the sensor node is selected as cluster-head. Then, the cluster-heads advertise to all sensor nodes to form the clusters. In the steady state phase, the sensors sense and transmit data to the cluster-heads. The cluster-heads aggregate data from the nodes in their cluster and then send it to the base station. After predefined periods, the network reselects its cluster-heads. By adopting cluster-based approach, we can efficiently conserve the power consumption and extend the system lifetime.

$$T(n) = \begin{cases} \dfrac{P}{1 - P[r \bmod (1/P)]} & \text{if } n \in G, \\ 0 & \text{otherwise,} \end{cases}$$

1.3.3 Genetic Algorithm

In [9], an optimization technique called Multi-Objective Genetic Algorithm (MOGA) is used with a simplified model to provide the end-user with a set of **Pareto-optimal** network designs with the **coverage** and **lifetime** of the network. The objective of the algorithm is to maximize the coverage and lifetime of the network, yielding a Pareto Front, from which the user can choose, as shown in Fig 1-3. The authors of [9] also discuss the influence of the ratio between the sensing range and the communication range on the optimal layout with the best coverage.

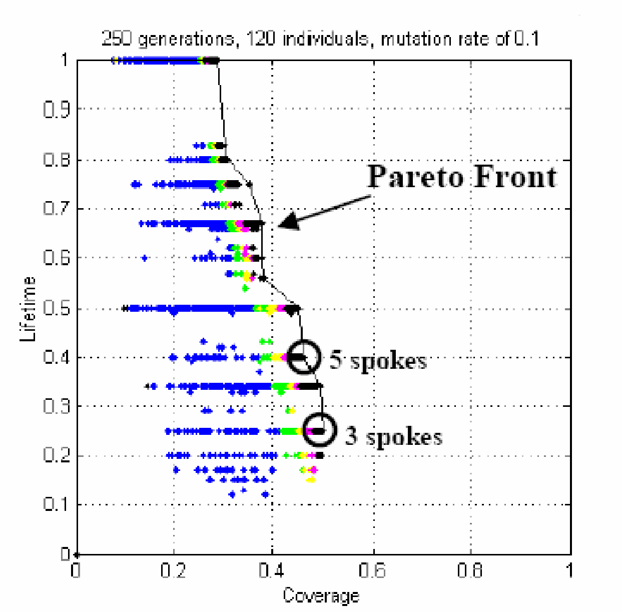


Figure 1-3. MOGA results for a WSN with 10 sensors and $R_{Sensor} = R_{Comm} = 2$

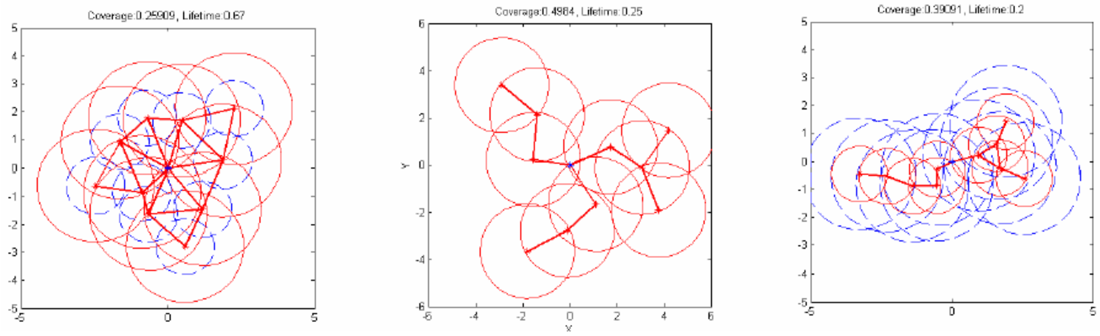


Figure 1-4. Layouts with best coverage for a WSN of 10 sensors and a ratio R_{Sensor} / R_{Comm} of 1/2 (left), 1 (middle) and 2 (right)

Chapter 2 Problem Formulation

2.1 Problem Description

In this paper, we consider the heterogeneous sensor networks consisting of data source nodes and communication nodes. The sensors are randomly scattered over the area of interest. The locations of the sensors are fixed and the base station knows them all a priori. The energy of the base station is assumed inexhaustible. The data source nodes periodically sense the environment, and the communication nodes aggregate the sensed data and then relay it to the sink node in each round of communication.

In the beginning of each round, the sink node broadcast routing information to all nodes and awakes the data source nodes to sense environment. Then, the awake data source nodes transmit the sensed data to the sink node through the data aggregation tree. To lower the energy consumption, we let each event be sensed by only one data source node in each round.

Because the battery capacity of sensors is fixed, the sensor nodes are highly energy-constrained. Therefore, the problem is to find a routing scheme to deliver information collected from data source nodes to the base station, which maximizes system lifetime. The system lifetime is defined as the number of rounds until the information about the occurrence of any of events can not be delivered to the sink node. Now, we have to decide the following decision variables: (1) the awake data source nodes to sense the environment in each round, (2) the data aggregation tree adopted to transmit the sensed data to the sink node in each round, (3) the number of times that each tree is used.

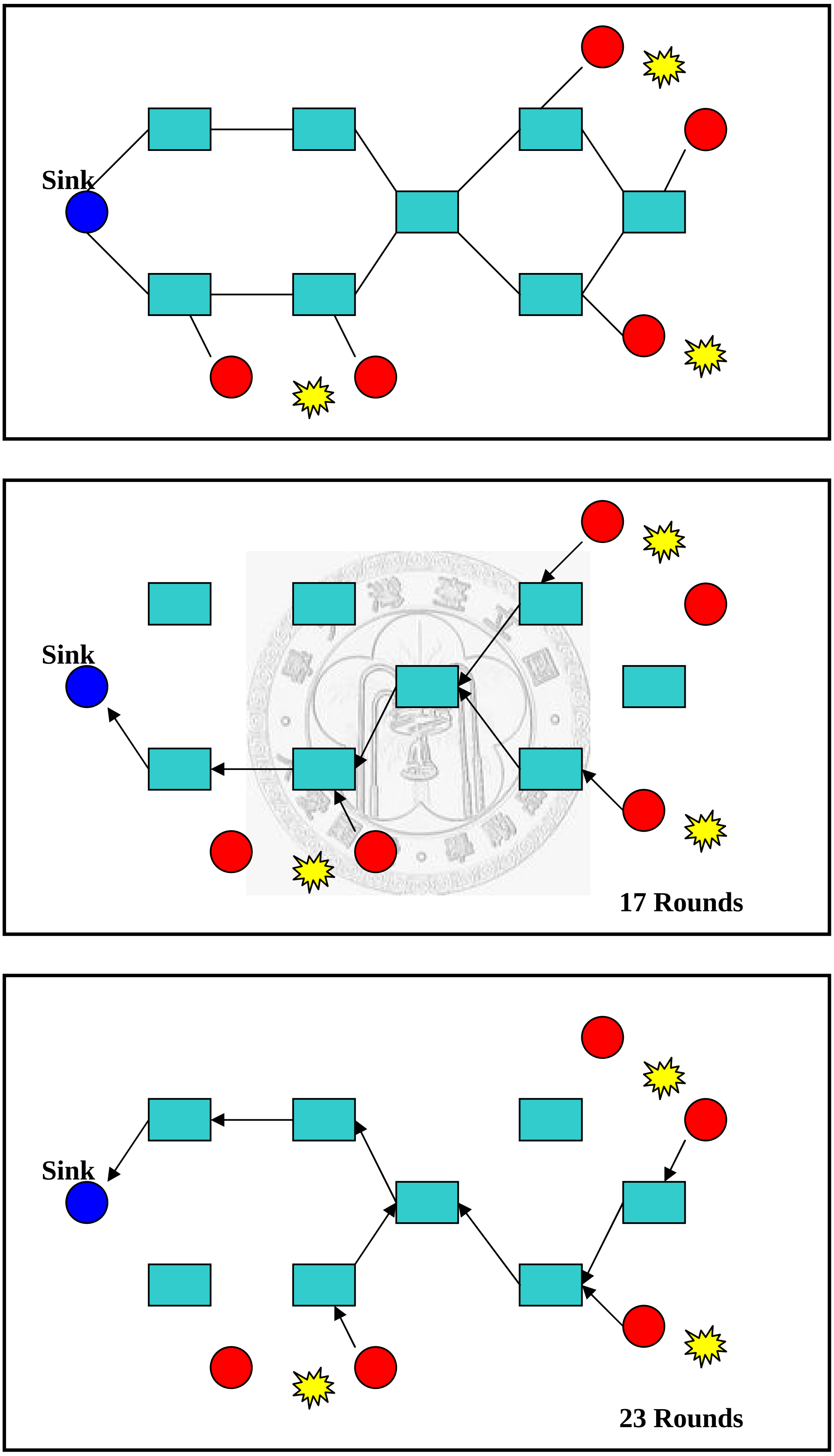


Figure 2-1. An illustrated example of network topology

Table 2-1. Problem Description

Problem Assumption

–Heterogeneous network

–Fixed sensing range and fixed transmission range

–Bidirectional links

–Error-free transmission within the transmission radius

-The sink node knows sensor nodes all a priori

Given

–The network topology including node set and link set

–The set of data source nodes in the network

–The set of communication nodes in the network

–The sink node in the network

–Capacity for each node evaluated by residual power lifetime

–Transmission cost of each link with respect to energy consumption

–Receiving cost of each link with respect to energy consumption

–Sensing cost of each link with respect to energy consumption

Objective

–To maximize the system lifetime of the sensor network

Subject to

–Event constraints: Each event must be monitored by one awake data source node and the awake data source nodes sense and transmit the sensed data to the sink node.

–Battery capacity constraint: The total energy consumption of a node can not exceed its initial energy level.

To determine

–The number of times that each tree t is used

2.2 Problem Notation (IP)

Table 2-2. Notation descriptions for given parameters (IP)

Given Parameters	
Notation	Description
T	The set of all spanning trees rooted at the source node
γ_{pn}	The indicator function which is 1 if relay node n is on the path p and 0 otherwise
N	The set of all communication nodes
W	The set of all data source nodes
L	The set of all links
C_n	The initial energy level of node n
E_r	The energy consumed for trees to receive one data unit of traffic over the link
E_S	The energy consumed for trees to transmit one data unit of traffic over the link
E_m	The energy consumed for source nodes to sense data
E_q	The energy consumed for all nodes to broadcast the routing information from the sink nodes to all nodes
e_{iw}	The indicator function which is 1 if the event i is in the coverage of the data source node w and 0 otherwise

R	The total number of rounds
V	The set of events
δ_{pl}	The indicator function which is 1 if the link *l* is on the path *p* and 0 otherwise
σ_{tl}	The indicator function which is 1 if the link *l* is on the tree *t* and 0 otherwise
P_w	The set of candidate paths from the data source node *w* to the sink node
o^+	The set of all outgoing links belonging to the node *o* $o \in \{N \cup W\}$
w^+	The set of all outgoing links belonging to the data source node *w*
s^-	The set of all incoming links belonging to the sink node *s*

Table 2-3. Notation descriptions for decision variables (IP)

Decision Variables	
Notation	Description
r_t	The number of times that tree t is used. $r_t \in \{0,\ 1,\ 2...,M_t\}$
π_{wr}	1 if the data source node *w* is awake in the round *r*, and 0 otherwise
ϕ_{nr}	1 if the communication node *n* is awake in the round *r*, and 0 otherwise
y_{lr}	1 if link *l* is used in round *r*, and 0 otherwise
z_{tr}	1 if the tree *t* is selected to transmit sensed data to the sink node in the round *r*, and 0 otherwise
x_{pr}	1 if the path *p* is selected to transmit sensed data to the sink node in the round *r*, and 0 otherwise

2.3 Problem Formulation (IP)

Objective Function

$$\max \sum_{t\in T} r_t \qquad \text{(IP)}$$

Subject to:

$$\sum_{w\in W} \pi_{wr} e_{iw} = 1 \qquad \forall i \in V, r \in R \qquad \text{(IP 1)}$$

$$\sum_{p\in P_w} x_{pr} = \pi_{wr} \qquad \forall r \in R, w \in W \qquad \text{(IP 2)}$$

$$\sum_{p\in P_w} x_{pr} \delta_{pl} \le y_{lr} \qquad \forall l \in L, r \in R, w \in W \qquad \text{(IP 3)}$$

$$\sum_{l\in o^+} y_{lr} \le 1 \qquad \forall o \in \left\{ N \bigcup W \right\}, r \in R \qquad \text{(IP 4)}$$

$$\pi_{wr} \le \sum_{l\in w^+} y_{lr} \qquad \forall w \in W, r \in R \qquad \text{(IP 5)}$$

$$\sum_{l\in s^-} y_{lr} \ge 1 \qquad \forall r \in R \qquad \text{(IP 6)}$$

$$\sum_{p\in P_w} x_{pr} \gamma_{pn} \le \phi_{nr} \qquad \forall n \in N, r \in R, w \in W \qquad \text{(IP 7)}$$

$$y_{lr} \le \sum_{t\in T} \sigma_{tl} z_{tr} \qquad \forall l \in L, r \in R \qquad \text{(IP 8)}$$

$$\sum_{t\in T} z_{tr} = 1 \qquad \forall r \in R \qquad \text{(IP 9)}$$

$$\sum_{r\in R} z_{tr} \le r_t \qquad \forall t \in T \qquad \text{(IP 10)}$$

The battery capacity constraints

$$\sum_{r\in R} E_q + \sum_{r\in R} \pi_{wr} \left(E_m + E_s \right) \le C_w \qquad \forall w \in W \qquad \text{(IP 11)}$$

$$\sum_{r\in R} E_q + \sum_{r\in R} \phi_{nr} \left(E_r + E_s \right) \le C_n \qquad \forall n \in N \qquad \text{(IP 12)}$$

The integer constraints

$$\pi_{wr} = 0 \text{ or } 1 \qquad \forall w \in W, r \in R \qquad \text{(IP 13)}$$

$$\phi_{nr} = 0 \text{ or } 1 \qquad \forall n \in N, r \in R \qquad \text{(IP 14)}$$

$$z_{tr} = 0 \text{ or } 1 \qquad \forall t \in T, r \in R \qquad \text{(IP 15)}$$

$y_{lr} = 0$ or 1 $\qquad \forall l \in L, r \in R$ (IP 16)

$x_{pr} = 0$ or 1 $\qquad \forall p \in P_w, w \in W, r \in R$ (IP 17)

$r_t \in \{0, 1, 2, ..., M_t\} \qquad \forall t \in T$. (IP 18)

The objective function is to **maximize the system lifetime of the given sensor network configuration**. The lifetime is defined as the total number of rounds. In each round, the awake data source nodes sense and transmit one data unit of traffic to the sink node through the tree *t*.

Constraint (IP 1): For each event *i* in the coverage of data source node *w*, it is necessary to be sensed by one awake data source node *w* in each round *r*.

Constraint (IP-2): For each awake data source node *w* in each round *r*, it has to select a path to transmit sensed data to the sink node.

Constraint (IP-3): It requires that if one path is selected for the data source node *w* in each round *r*, it must also be on the subtree adopted by the source node *w*.

Constraint (IP-4): We select at most one outgoing link of node in each round *r*.

Constraint (IP 5): We select exactly one outgoing link of the data source node in each round *r*.

Constraint (IP 6): The number of incoming links of the sink node in each round *r* must be larger than 1.

Constraint (IP 7): It requires that if one path is selected for the data source node *w* in each round *r*, it must also be on the subtree adopted by the source node *w*.

Constraint (IP 8): It requires that the subtree adopted by any source node *w* be a subset of the shared spanning tree. This shared spanning tree is selected to be shared by the source nodes.

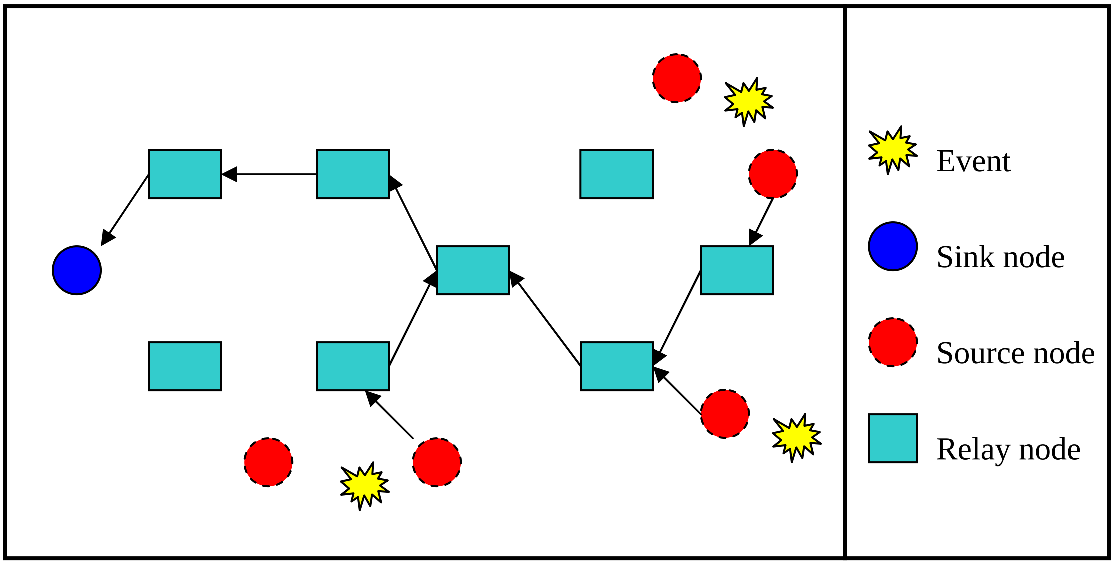


Figure 2-2. An illustrated example of Constraints (IP 1)-(IP 8)

Constraint (IP 9): In each round *r*, a tree must be selected to transmit information to the sink node.

Constraint (IP 10): After *r* rounds, the total number of times r_t that tree *t* is used to transmit data to the sink node.

Constraint (IP 11): For each communication node *w*, the total receiving and communication power consumption can not exceed its initial energy level.

Constraint (IP 12): For each data source node *w*, the total sensing and communication power consumption can not exceed its initial energy level.

Constraint (IP 13)-(IP 18): The integer constraints for decision variables π_{wr}, ϕ_{nr}, z_{tr}, y_{lr}, x_{pr}, and r_t.

Chapter 3 Solution Approach

3.1 Introduction to Lagrangean Relaxation Method

Lagrangean Relaxation method was widely used for scheduling and solving integer programming programming problems in the 1970s, because it is flexible and provides excellent solutions for these problems [5]. Therefore, it has become one of the best tools for solving optimization problems, such as integer programming, linear programming with combinatorial objective function, and non-linear programming.

By adopting Lagrangean Relaxation method, there are several advantages. In the beginning, we relax the complicated constraints of the primal mathematical formulation and form a new Lagrangean Relaxation problem in many different ways. By relaxing the complicated constraints and putting them in the objective function with the corresponding Lagrangean multipliers, we can divide the original problem into several independent and easily solvable sub-problems. After that, for each sub-problem, we detect the underlying structure and properties and solve it optimally in some well-known algorithms.

By solving the Lagrangean Relaxation problem, we can get a boundary to the objective function of the original problem. The solution of the Lagrangean Relaxation problem is always a lower bound (to the original minimization problem). Then, we use the boundary to design a heuristic approach to get a primal feasible solution. To solve the original problem optimally and minimize the gap between the primal problem and the Lagrangean Relaxation problem, we improve the lower bound by solving the sub-problems optimally and using the subgradient method to adjust the multipliers at each iteration.

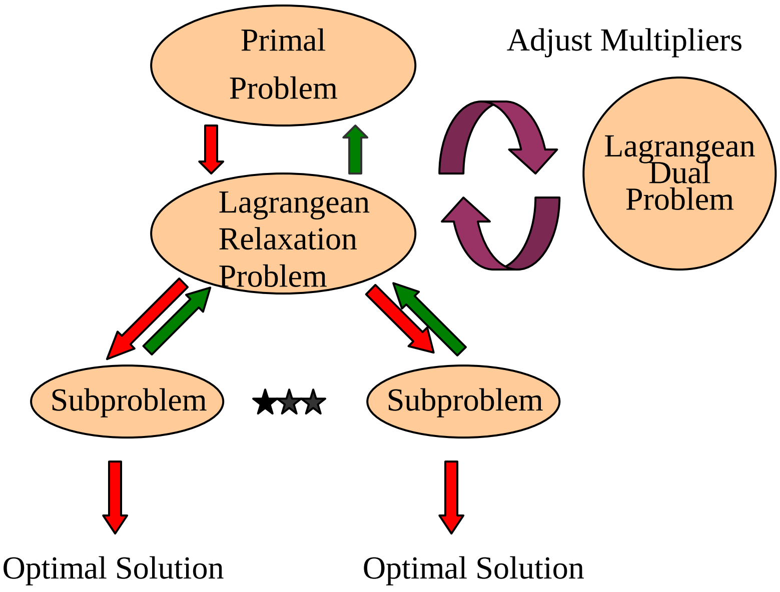


Figure 3-1. Illustration of the Lagrangean Relaxation Method

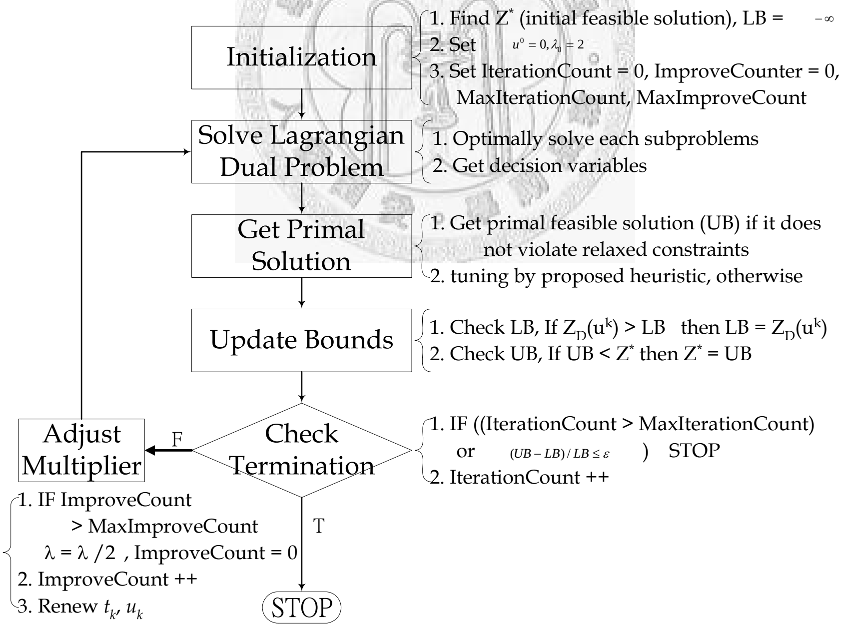


Figure 3-2. Procedures of the Lagrangean Relaxation Method

3.2 Lagrangean Relaxation (LR)

By adopting Lagrangean Relaxation method, we can transform the primal problem (IP) into the following Lagrangean Relaxation problem (LR) where constraints (3)、(5)、(7)、(8)、(11)、(12) are relaxed. As a convention, we first multiple the objective function of the primal problem with minus one and transform it into a minimization problem. For a vector of non-negative multipliers, we present the Lagrangean Relaxation problem as follows:

$$
\begin{aligned}
& z_{LR1} = \left(\mu^1, \mu^2, \mu^3, \mu^4, \mu^5, \mu^6\right) \\
& \min - \sum_{t \in T} \left(r_t\right) \\
& + \sum_{l \in L} \sum_{r \in R} \sum_{w \in W} \mu^1_{lrw} \left(\sum_{p \in P_w} x_{pr} \delta_{pl} - y_{lr} \right) \\
& + \sum_{w \in W} \sum_{r \in R} \mu^2_{wr} (\pi_{wr} - \sum_{l \in w^+} y_{lr}) \\
& + \sum_{n \in N} \sum_{r \in R} \sum_{w \in W} \mu^3_{nrw} (\sum_{p \in P_w} x_{pr} \gamma_{pn} - \phi_{nr}) \\
& + \sum_{l \in L} \sum_{r \in R} \mu^4_{lr} \left(y_{lr} - \sum_{t \in T} \sigma_{tl} z_{tr} \right) \\
& + \sum_{w \in W} \mu^5_{w} (\sum_{r \in R} E_q + \sum_{r \in R} \pi_{wr} \left(E_m + E_s\right) - C_w) \\
& + \sum_{n \in N} \mu^6_{n} (\sum_{r \in R} E_q + \sum_{r \in R} \phi_{nr} \left(E_R + E_s\right) - C_n)
\end{aligned}
\tag{LR}
$$

Subject to:

$$\sum_{w \in W} \pi_{wr} e_{iw} = 1 \qquad \forall i \in V, r \in R \tag{LR 1}$$

$$\sum_{p \in P_w} x_{pr} = \pi_{wr} \qquad \forall r \in R, w \in W \tag{LR 2}$$

$$\sum_{l \in o^+} y_{lr} \le 1 \qquad \forall o \in \left\{N \bigcup W\right\}, r \in R \tag{LR 3}$$

$$\sum_{l \in s^-} y_{lr} \ge 1 \qquad \forall r \in R \qquad \text{(LR 4)}$$

$$\sum_{t \in T} z_{tr} = 1 \qquad \forall r \in R \qquad \text{(LR 5)}$$

$$\sum_{r \in R} z_{tr} \le r_t \qquad \forall t \in T \qquad \text{(LR 6)}$$

$$\pi_{wr} = 0 \text{ or } 1 \qquad \forall w \in W, r \in R \qquad \text{(LR 7)}$$

$$\phi_{nr} = 0 \text{ or } 1 \qquad \forall n \in N, r \in R \qquad \text{(LR 8)}$$

$$z_{tr} = 0 \text{ or } 1 \qquad \forall t \in T, r \in R \qquad \text{(LR 9)}$$

$$y_{lr} = 0 \text{ or } 1 \qquad \forall l \in L, r \in R \qquad \text{(LR 10)}$$

$$x_{pr} = 0 \text{ or } 1 \qquad \forall p \in P_w, w \in W, r \in R \qquad \text{(LR 11)}$$

$$r_t \in \{0, 1, 2, \ldots, M_t\} \qquad \forall t \in T. \qquad \text{(LR 12)}$$

We can further decompose this LR problem into 4 independent subproblems according to different decision variables.

3.4.1 Subproblem 1 (related to decision variable x_{pr} 、 π_{wr})

$$\min \sum_{l\in L}\sum_{r\in R}\sum_{w\in W}\mu^1_{lrw}\left(\sum_{p\in P_w} x_{pr}\delta_{pl}\right)+\sum_{w\in W}\sum_{r\in R}\mu^2_{wr}\left(\pi_{wr}\right)$$

$$+\sum_{n\in N}\sum_{r\in R}\sum_{w\in W}\mu^3_{nrw}\left(\sum_{p\in P_w}x_{pr}\gamma_{pn}\right)+\sum_{w\in W}\sum_{r\in R}\mu^6_{wr}\left(\pi_{wr}\right)\left(E_m+E_s\right)$$

$$=\min\sum_{w\in W}\sum_{r\in R}\sum_{p\in P_w}\left(\sum_{l\in L}\mu^1_{lrw}\delta_{pl}+\sum_{n\in N}\mu^3_{nrw}\gamma_{pn}\right)x_{pr}+\sum_{w\in W}\sum_{r\in R}\left[\mu^2_{wr}+\mu^5_{w}\left(E_m+E_s\right)\right]\pi_{wr}$$

Subject to:

$\sum_{p\in P_w} x_{pr}=\pi_{wr}$ $\quad \forall w\in W, r\in R$ (Sub1 1.1)

π_{wr} = 0 or 1 $\quad \forall w\in W, r\in R$ (Sub1 1.2)

x_{pr} = 0 or 1 $\quad \forall p\in P_w, w\in W, r\in R$ (Sub1 1.3)

$\sum_{w\in W}\pi_{wr}e_{iw}=1$ $\quad \forall w\in W, r\in R$. (Sub1 1.4)

The proposed algorithm for solving (Sub1) is described as follows:

Step1: For each source node *w*, we compute the coefficient $\left(\mu^2_{wr}+\mu^5_{w}\left(E_m+E_s\right)\right)$ for each π_{wr}.

Step2: If the corresponding coefficient is negative, we set π_{wr} to 1; otherwise, we set π_{wr} to 0.

Step3: If π_{wr} is equal to 1, we find the shortest path with nonnegative arc weights $(\sum_{l\in L}\mu^1_{lrw}\delta_{pl}+\sum_{n\in N}\mu^3_{nrw}\gamma_{pn})$ by the Dijkstra's algorithm. Repeat step 3 for all π_{wr}.

The computational complexity of above algorithms is $O\left(\left|W+N\right|^2\right)$

3.4.2 Subproblem 2 (related to decision variable y_{lr})

$$\min \sum_{l\in L}\sum_{r\in R}\sum_{w\in W}\mu^1_{lrw}\left(-y_{lr}\right)-\sum_{w\in W}\sum_{r\in R}\mu^2_{wr}\left(\sum_{l\in w^+}y_{lr}\right)+\sum_{l\in L}\sum_{r\in R}\mu^4_{lr}y_{lr}$$

$$=\sum_{r\in R}\left[\sum_{l\in L}\left(\mu^4_{lr}-\sum_{w\in W}\mu^1_{lrw}\right)-\sum_{l\in w^+}\sum_{w\in W}\mu^2_{wr}\right]y_{lr}$$

Subject to:

$$\sum_{l\in o^+}y_{lr}\le 1 \qquad \forall o\in\left\{N\bigcup W\right\}, r\in R \qquad \text{(Sub2 2.1)}$$

$$\sum_{l\in s^-}y_{lr}\ge 1 \qquad \forall r\in R \qquad \text{(Sub2 2.2)}$$

$$y_{lr} = 0 \text{ or } 1 \qquad \forall l\in L, r\in R. \qquad \text{(Sub2 2.3)}$$

The proposed algorithm for solving (Sub2) is described as follows:

Step1: For each link, we compute the coefficient $\left(\mu^4_{wr}-\sum_{l\in L}\mu^1_{lwr}\right)$. If the link is the outgoing link of the source node, the corresponding coefficient is set to $\left(\mu^4_{lr}-\sum_{w\in W}\mu^1_{lrw}-\sum_{w\in W}\mu^2_{wr}\right)$.

Step2: For all outgoing links of node, we find the smallest coefficient. If the smallest coefficient is negative then we set the corresponding y_{lr} to 1 and the other outgoing links y_{lr} to 0, otherwise we set all outgoing link y_{lr} to 0. Repeat step 2 for all nodes.

Step3: For all incoming links of the sink node, we find the smallest coefficient and set the corresponding y_{lr} to 1 and the other incoming links y_{lr} to 0.

The computational complexity of above algorithm is $O\left(|W|\right)$ for each link.

3.4.3 Subproblem 3 (related to decision variable z_{tr} 、 r_t)

$$\min -\sum_{t\in T} r_t + \sum_{l\in L}\sum_{r\in R}\mu_{lr}^4\left(-\sum_{t\in T}\sigma_{tl} z_{tr}\right)$$
$$= -\sum_{t\in T} r_t - \sum_{r\in R}\sum_{t\in T}\left(\sum_{l\in L}\mu_{lr}^4\sigma_{tl}\right) z_{tr}$$

Subject to:

$$\sum_{t\in T} z_{tr} = 1 \qquad \forall r\in R \qquad \text{(Sub3 3-1)}$$

$$z_{tr} = 0 \text{ or } 1 \qquad \forall t\in T,\, r\in R \qquad \text{(Sub3 3-2)}$$

$$\sum_{r\in R} z_{tr} \le r_t \qquad \forall t\in T \qquad \text{(Sub3 3-3)}$$

$$r_t \in \{0,1,2,\ldots,M_t\} \qquad \forall t\in T\,. \qquad \text{(Sub3 3-4)}$$

The proposed algorithm for solving (Sub3) is described as follows:

Step1: For each z_{tr}, we solve the maximum cost spanning tree problem with nonnegative arc weights μ_{lr}^4 by Prim’s algorithm.

Step2: We compute the sum of the number of the rounds that each tree *t* is used.

The computational complexity of above algorithm is $O\left(|W+N|^2\right)$ for each tree.

3.4.4 **Subproblem 4** (related to decision variable ϕ_{nr})

$$\min \sum_{n\in N}\sum_{r\in R}\sum_{w\in W}\mu_{nrw}^{3}\left(-\phi_{nr}\right)+\sum_{n\in N}\sum_{r\in R}\mu_{nr}^{7}\phi_{nr}\left(E_r+E_s\right)$$
$$=\min \sum_{n\in N}\sum_{r\in R}\left(\mu_{n}^{6}\left(E_r+E_s\right)-\sum_{w\in W}\mu_{nrw}^{3}\right)\phi_{nr}$$

Subject to:

ϕ_{nr} = 0 or 1 $\forall n\in N, r\in R$. (Sub4 4-1)

This problem can be further decomposed into $|N|\times|R|$ independent subproblems and solved optimally by a simple algorithm. For each communication node *n* in each round *r*, we first compute the coefficient $\left(\mu_{nr}^{6}\left(E_r+E_s\right)-\sum_{w\in W}\mu_{nrw}^{3}\right)$. Then, if the coefficient is negative, we set ϕ_{nr} to 1; otherwise we set ϕ_{nr} to 0.

The computational complexity is $O(|W|)$ for each communication node.

3.3 The Dual Problem and the Subgradient Method (IP)

According to the algorithms proposed above, we could effectively solve the Lagrangean Relaxation problem optimally. Based on the weak Lagrangean duality theorem (for any given set of nonnegative multipliers, the optimal objective function value of the corresponding Lagrangean Relaxation problem is a lower bound on the optimal objective function value of the primal problem [1]), $Z_D\left(\mu^1,\mu^2,\mu^3,\mu^4,\mu^5,\mu^6\right)$ is a lower bound on Z_{IP}. We construct the following dual problem to calculate the tightest lower bound and solve the dual problem by using the subgradient method.

Dual Problem

$Z_D = \max Z_D\left(\mu^1,\mu^2,\mu^3,\mu^4,\mu^5,\mu^6\right)$

Subject to:

$\mu^1,\mu^2,\mu^3,\mu^4,\mu^5,\mu^6 \ge 0$.

Let the vector S be a subgradient of $Z_D\left(\mu^1,\mu^2,\mu^3,\mu^4,\mu^5,\mu^6\right)$ at $\left(\mu^1,\mu^2,\mu^3,\mu^4,\mu^5,\mu^6\right)$. In iteration *k* of the subgradient optimization procedure, the multiplier vector $m^k=\left(\mu^{1k},\mu^{2k},\mu^{3k},\mu^{4k},\mu^{5k},\mu^{6k}\right)$is updated by $m^{k+1}=m^k+\alpha^k S^k$.

The step size α^k is determined by $\delta\dfrac{Z_{IP}^k - Z_D\left(m^k\right)}{\left\|S^k\right\|^2}$, where Z_{IP}^k is the best primal objective function value found by iteration *k* (an upper bound on the optimal primal objective function value), and δ is a constant$\left(0\le\delta\le 2\right)$.

Chapter 4 Getting Primal Feasible Solutions

4.1 Lagrangean Relaxation Results

By applying Lagrangean Relaxation method and the subgradient method to solve our complex problem, we can obtain a theoretical lower bound of the primal problem and some hints to get a feasible solution to the primal problem. Because some difficult constraints of the primal problem are relaxed by using Lagrangean Relaxation method, we can not guarantee that the consolidated result of the Lagrangean Relaxation problem is feasible to the primal problem. We have to ensure that it is a feasible solution, which is satisfied with all constraints of the primal problem, if not, we have to make some modifications.

4.2 Getting Primal Feasible Solutions

The heuristic constructs data aggregation tress based on the solutions to (Sub1) and (Sub3). By designating Z_{tr}, and π_{wr}, we can obtain the data aggregation trees. Then, we eliminate the redundant trees to construct candidate trees. In the beginning, we choose the data aggregation tree from the candidate trees with the lowest cost, which is evaluated as the total energy consumption in the data aggregation tree, to transmit information. After a certain rounds, some nodes are drained of their energy; we select another tree from the candidate tress to transmit the information. When the candidate trees are exhausted, we reconstruct a data aggregation tree to transmit the information based on the remaining energy of nodes. The procedure of heuristic is shown in Table 4-1 and the complete Lagrangean Relaxation based algorithm is shown in Table 4-2.

Table 4-1. Getting Primal Heuristic Algorithm

Step1: We construct the candidate trees according to the decision variables, namely Z_{tr}, and π_{wr}.

Step2: We sort the candidate trees in ascending order according to the cost, which is evaluated as the total energy consumption in the data aggregation tree.

Step3: We use the aggregation tree from the candidate trees and calculate the energy consumption of nodes, if satisfied with all constraints; if not, we select another aggregation tree. Repeat Step3 until the candidate trees are exhausted.

Step4: We reconstruct an aggregation tree based on the remaining energy of nodes and use it to transmit information. Then, we calculate the energy consumption of nodes. Repeat Step4 until we can not find the aggregation tree to transmit information.

Step5: Finally, we can obtain system lifetime.

Table 4-2. Lagrangean Relaxation based Algorithm

```
begin
    Initialize the Lagrangean multiplier vector ($V^1, V^2, V^3, V^4, V^5, V^6$) to be
    all zero vectors;
    UB := 0; LB:= - Iinfinity;
    improve_counter := 0;
    step_size_cofficient := 2;
    for iteration := 1 to Max_Iteration_Number do
    begin
        run subproblem (Sub1)
        run subproblem (Sub2)
        run subproblem (Sub3)
        run subproblem (Sub4)
        calculate Zdu;
        if Zdu> LB then
            LB := Zdu; improve_counter +1;
            improve_counter := 0; $\delta$ := $\delta / 2$;
        run Primal_Heuristic_Algortihm;
        if ZIP < UB then UB = ZIP;
        run update-step-size;
        run update-Lagrangean-multiplier;
    end;
end;
```

4.3 Simple Heuristic Algorithms

According to [3], we implement **Power Efficient Data gathering and Aggregation Protocol (PEDAP)** Algorithm as Simple Algorithm 1 (SA1), and **Power Efficient Data gathering and Aggregation Protocol-Power Aware (PEDAP-PA)** Algorithm as Simple Algorithm 2 (SA2). The system lifetime of these algorithms is defined as the number of rounds until the information about the occurrence of any of events can not be delivered to the sink node.

We will compare the solution quality of Lagrangean Relaxation based algorithm (LR) with those of these simple heuristic algorithms (SAs) in Chapter 5.

Chapter 5 Computational Experiments

5.1 Experiment Environment

In this chapter, we conduct several experiments with different parameters to evaluate the solution quality of our solution approach. In the following, we experiment different number of data source nodes with different number of nodes in random and grid network topologies to evaluate the gap (%) of the result of LR and compare it with those of the SAs.

The test platform is a PC with Pentium4 2.4G CPU and 512MB DRAM. We execute our program on Windows 2000 and Virtual C++ 6.0. The program is written in programming language C++.

Table 5-1. Parameters of Lagrangean Relaxation based algorithm

Number of iterations	1000
Improvement counter	25
Begin to get primal feasible solution	1
Initial upper bound	0
Initial scalar of step size	2
Stopping step size	10^{-6}

Table 5-2. Parameters of cases

Number of nodes	16~81 (depend on each case)
Region	250×250 unit square
Transmission radius	40~60 (depend on each case)
Geographic position x-axis	0~250 unit
Geographic position y-axis	0~250 unit
Initial energy capacity of nodes	0.5~1.0 J

The parameters listed in Table 5-1 and Table 5-2 are used for the all cases of experiment. To maintain the connectivity, we set the transmission radius larger in the small network.

We denote the dual solution as “ Zdu “, and Lagrangean Relaxation based heuristic as “ ZIP ”. “Gap” is used to evaluate our solution quality. $Gap = \left|\frac{ZIP - Zdu}{Zdu}\right| * 100\%$. “Improvement Ratio” is used to compare the Lagrangean Relaxation based algorithm with the simple algorithms. Improvement Ratio $= \left|\frac{ZIP - SA}{SA}\right| * 100\%$.

5.2 Random Network

5.2.1 Network Topology

In random network, sensors are randomly scattered over the area of interest. The network topology is shown in Fig. 5-1. In our experiments, each event is covered by at least two data source nodes and one of them senses and transmits the information to the sink node in each round of communication.

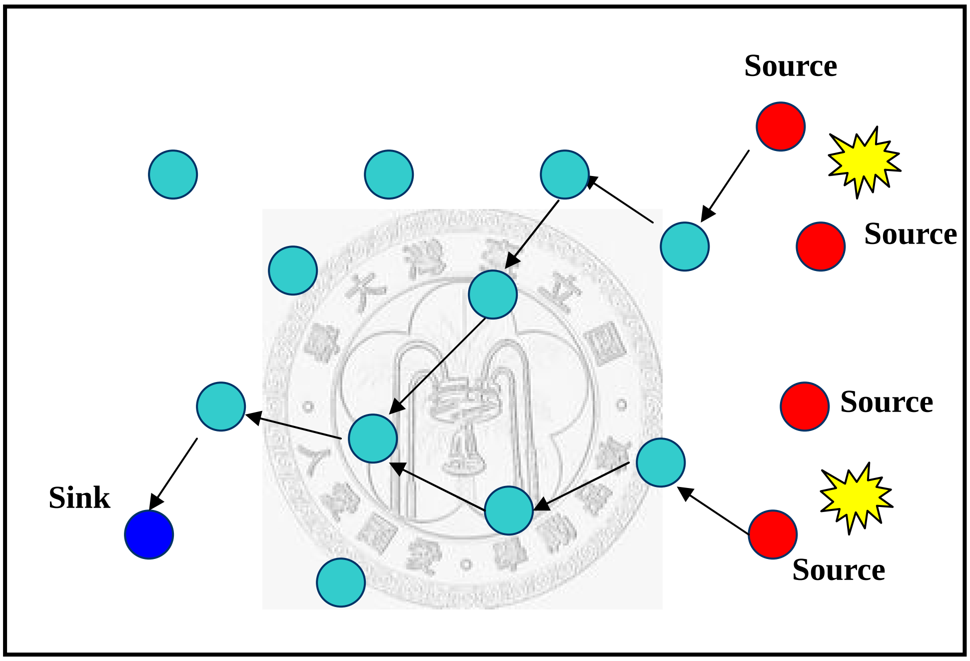


Figure 5-1. Random Network Topology

5.2.2 Solution Quality

To make the comparison easier, solutions to the minimization problem are transformed into solutions to the original maximization problem.

Table 5-3. Evaluation of gap (%) and improvement ratios
by given different number of nodes and data source nodes in random network

No. of Nodes	Events	Sources	Zdu	ZIP	Gap (%)	SA1	Imp. Ratio to SA1 (%)	SA2	Imp. Ratio to SA2 (%)
16	1	2	75.42	71	6.23	34	108.82	39	82.05
	2	5	76.54	71	7.80	34	108.82	39	82.05
25	1	2	93.31	89	4.84	50	78.00	51	74.51
	2	5	93.52	89	5.08	48	85.42	49	81.63
	4	10	87.16	81	7.60	48	68.75	48	68.75
36	1	2	111.20	106	4.91	34	211.76	31	241.94
	2	5	111.93	106	5.60	29	265.52	30	253.33
	4	10	83.65	79	5.89	29	172.41	30	163.33
49	1	2	83.15	79	5.25	39	102.56	41	92.68
	2	5	83.68	79	5.93	39	102.56	41	92.68
	4	10	84.92	79	7.49	39	102.56	41	92.68
	8	20	74.34	68	9.32	37	83.78	37	83.78
64	1	2	100.22	96	4.40	40	140.00	43	123.26
	2	5	99.66	94	6.02	40	135.00	45	108.89
	4	10	94.71	89	6.41	40	122.50	43	106.98
	8	20	85.15	79	7.79	40	97.50	41	92.68
	16	30	86.95	79	10.06	42	88.10	40	97.50
81	1	2	93.16	90	3.52	44	104.55	36	150.00
	2	5	93.42	90	3.80	44	104.55	36	150.00
	4	10	94.51	90	5.01	43	109.30	33	172.73
	8	20	47.04	45	4.52	39	15.38	31	45.16
	16	30	47.81	45	6.23	39	15.38	31	45.16
	24	40	46.82	45	4.04	39	15.38	31	45.16

Then, we summarize the above experiment results into diagrams and show them in Figure 5-2, Figure 5-3, and Figure 5-4.

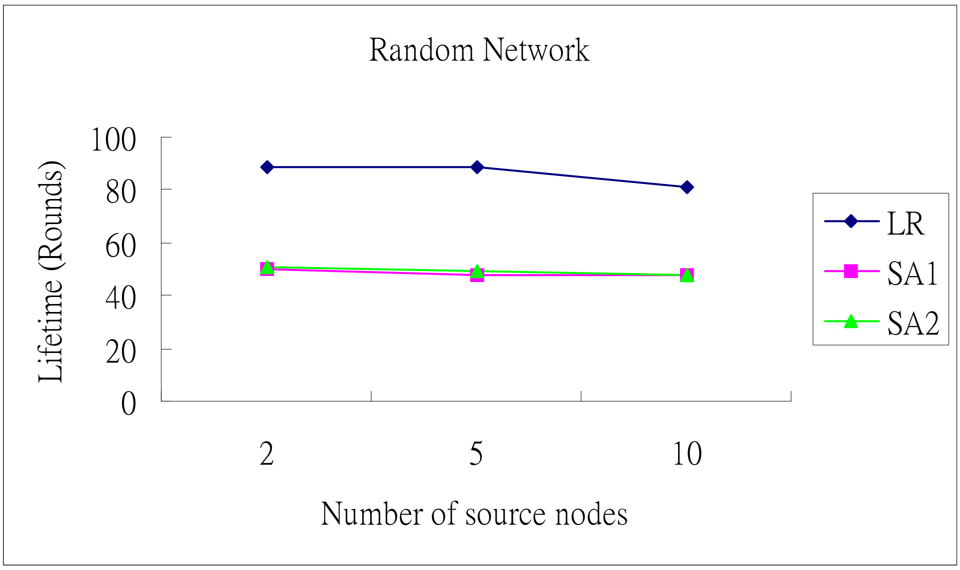


Figure 5-2. Evaluation of lifetime (Rounds) in random network

(Small Network, Number of Nodes = 25)

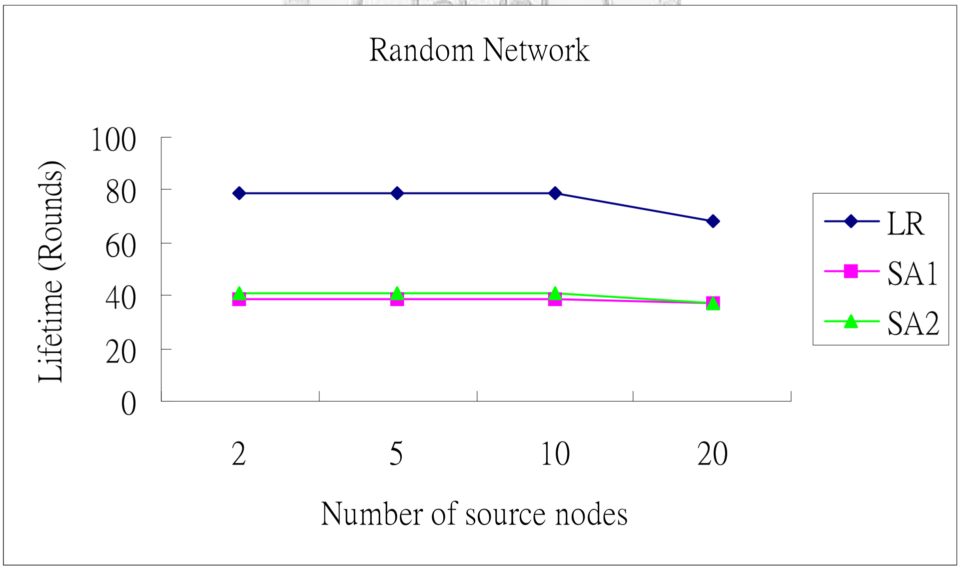


Figure 5-3. Evaluation of lifetime (Rounds) in random network

(Medium Network, Number of Nodes = 49)

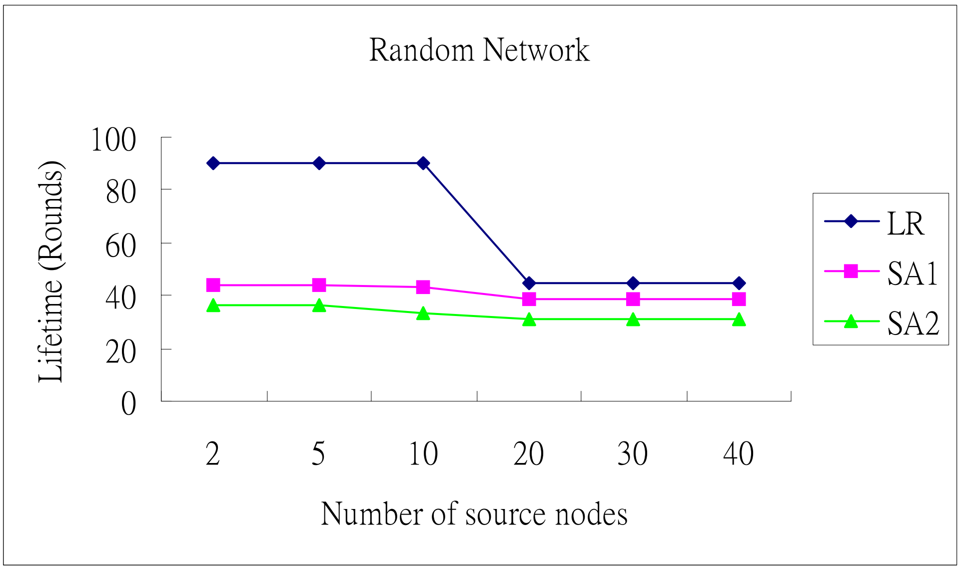


Figure 5-4. Evaluation of lifetime (Rounds) in random network

(Large Network, Number of Nodes = 81)

In Table 5-1, we can observe that the gap of our solutions is small, which means our solution quality is near optimal. Moreover, our Lagrangean Relaxation based algorithm always outperforms simple heuristic algorithms in different size of network. The improvement ratios shown in Table 5-1 indicate that our LRs is much more energy efficient than SAs.

5.3 Grid Network

5.3.1 Network Topology

In the experiments, we distribute sensor nodes in grid topology, as shown in Figure 5-5. Each event is covered by at least two data source nodes and one of them senses and transmits the information to the sink node in each round of communication.

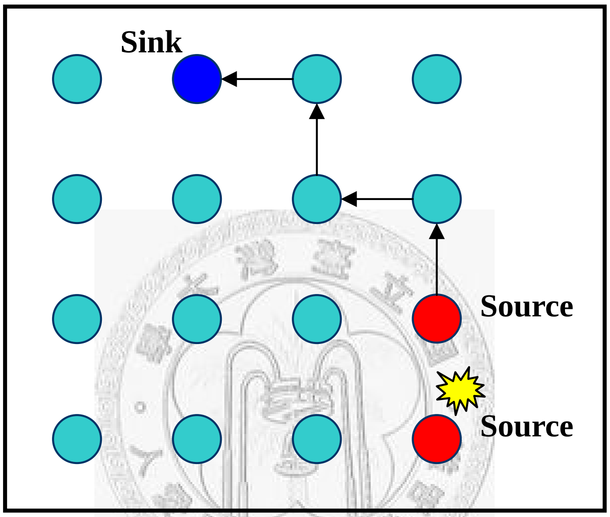


Figure 5-5. Grid Network Topology

5.3.2 Solution Quality

To make the comparison easier, solutions to the minimization problem are also transformed into solutions to the original maximization problem.

Table 5-4. Evaluation of gap (%) and improvement ratios
by given different number of nodes and data source nodes in grid network

No. of Nodes	Events	Sources	Zdu	ZIP	Gap (%)	SA1	Impr. Ratio to SA1 (%)	SA2	Imp. Ratio to SA2 (%)
16	1	2	90.49	86	5.22	49	75.51	47	82.98
	2	5	81.35	80	1.68	43	86.05	43	86.05
25	1	2	98.77	92	7.36	47	95.74	46	100.00
	2	5	86.54	82	5.54	42	95.24	39	110.26
	4	10	88.25	82	7.63	42	95.24	33	148.48
36	1	2	112.67	108	4.33	61	77.05	46	134.78
	2	5	89.53	84	6.58	49	71.43	46	82.61
	4	10	91.99	84	9.51	27	211.11	45	86.67
49	1	2	85.77	81	5.89	48	68.75	48	68.75
	2	5	86.87	81	7.24	48	68.75	48	68.75
	4	10	63.04	63	0.06	36	75.00	36	75.00
	8	20	48.19	44	9.52	36	22.22	36	22.22
64	1	2	89.98	85	5.86	45	88.89	39	117.95
	2	5	90.64	85	6.63	45	88.89	39	117.95
	4	10	92.62	85	8.97	45	88.89	40	112.50
	8	20	46.28	45	2.83	41	9.76	41	9.76
81	1	2	85.51	80	6.89	53	50.94	54	48.15
	2	5	87.00	79	10.13	53	49.06	53	49.06
	4	10	83.27	79	5.41	52	51.92	53	49.06
	8	20	69.90	61	14.59	52	17.31	53	15.09

Then, we summarize the above experiment results into diagrams and show them in Figure 5-6, Figure 5-7, and Figure 5-8.

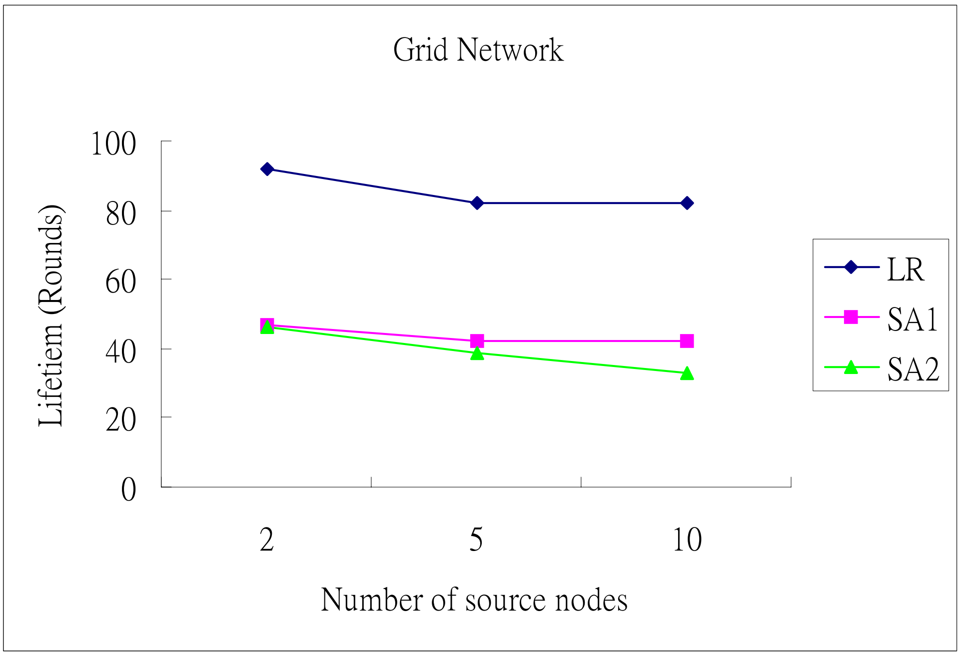


Figure 5-6. Evaluation of lifetime (Rounds) in grid network

(Small Network, Number of Nodes = 25)

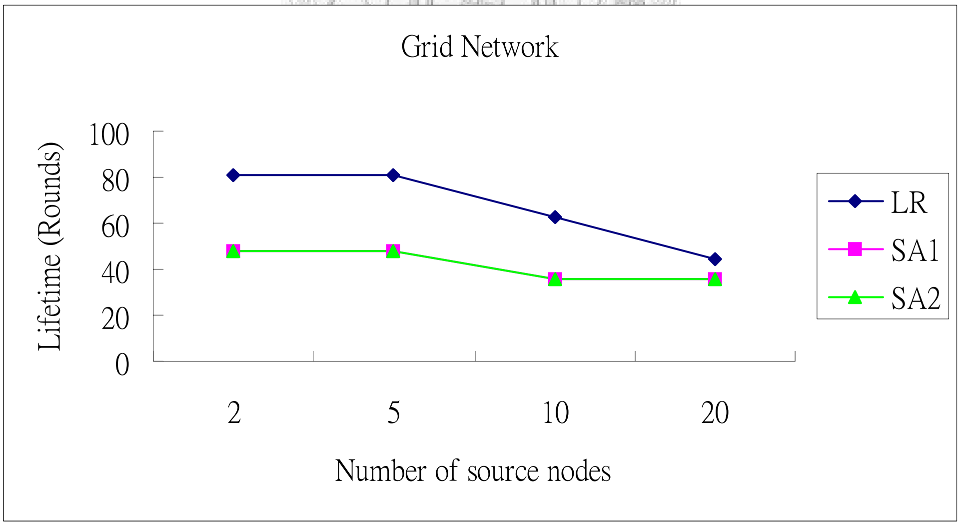


Figure 5-7. Evaluation of lifetime (Rounds) in grid network

(Medium Network, Number of Nodes = 49)

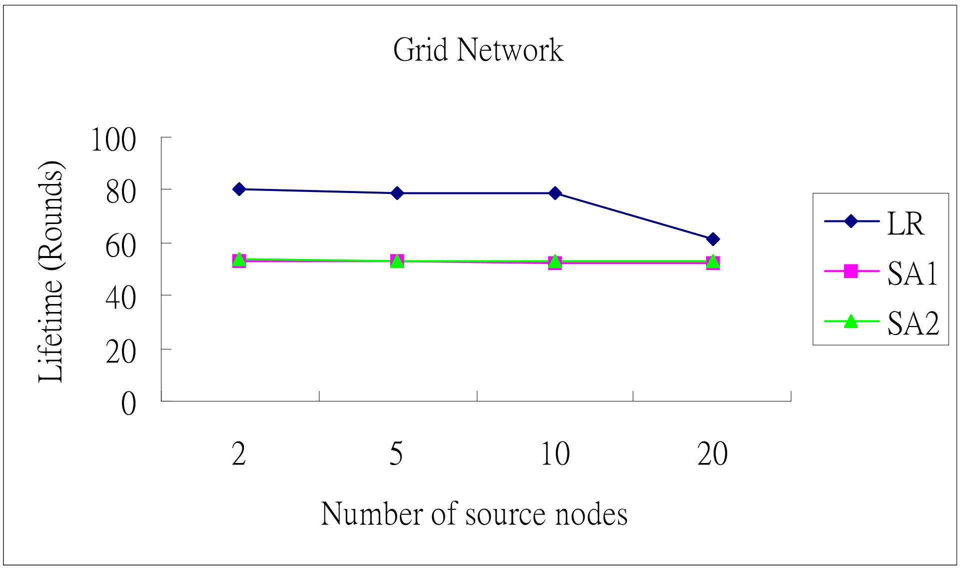


Figure 5-8. Evaluation of lifetime (Rounds) in grid network

(Large Network, Number of Nodes = 81)

In Table 5-2, we can find that the gap is also small, which means we obtain near optimal solutions in the grid network. Moreover, our solutions quality of Lagrangean Relaxation based algorithm is always superior to those of simple heuristic algorithms. The improvement ratios shows that our LRs is much more energy efficient than SAs.

5.4 Result Discussion

According to the experiment results, we can find that our Lagrangean Relaxation based algorithm always outperforms the simple heuristic algorithms. The reason is that we adopt dynamic data source node concept. We awake only one data source node to sense an event in each round; thus, we can reserve the energy the sensor nodes consume to sense and transmit the information of the same event to the sink node and further extend the system lifetime.

With the fixed network size, as the number of data source nodes increases, the system lifetime shortens. Since the energy consumers increase, the total energy consumption increases. However, we can observe that the lifetime declining trend is not a linear function but a step function. That is because some nodes play an important role in the routing of wireless sensor networks. Once these nodes are draining of their energy, the network becomes disconnected and then can not transmit information. We call them articulation points. Only when the increasing traffic with the increasing number of nodes exceeds the load of the articulation points does the system lifetime decline. In Fig 5-2, the marked node is the articulation point.

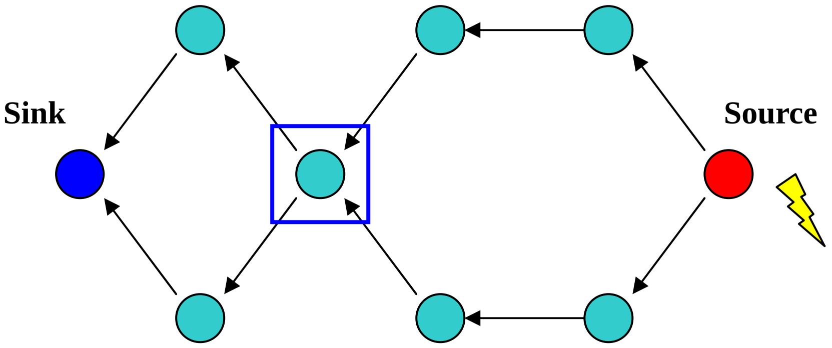


Figure 5-9. An illustrated example of Articulation Points

Chapter 6 Conclusion and Future Work

6.1 Conclusion

Wireless sensor networks consisting of small devices with sensing, computation, and wireless communications capacities will become increasingly widespread due to the rapid advancements in microprocessor, memory, and radius techniques. However, energy awareness is an essential design issue, because it is infeasible to recharge the batteries of the nodes in severe environments. By adopting data-centric routing, we can decrease the communications and further reduce the total energy consumption. In this thesis, we address the construction of a data aggregation tree in different round of communication in heterogeneous sensor networks and maximize the system lifetime. Nevertheless, how to construct an energy-efficient data aggregation tree in each round is a difficult problem to solve. To solve this problem, we have proposed a solution approach based on Lagrangean Relaxation based algorithm to construct candidate aggregation trees and carefully allocate them in different round of communication in order to maximize the system lifetime.

Our major contribution in this thesis is that we propose a mathematical formulation to well model the energy-efficient data-centric routing design problem and apply Lagrangean Relaxation and subgradient method to solve it. Then, we devise a heuristic approach to get feasible solutions. Finally, we conduct several experiments in different network topologies. According to these experiment results, we can claim that our LR based algorithm is superior to the PEDAP and PEDAP-PA algorithms.

6.2 Future Work

In this thesis, we consider the construction of data aggregation trees in different round of communication in heterogeneous sensor networks under energy capacity constraints. However, QoS property is a fundamental consideration for critical events, such as maximum end-to-end delay. However, energy-efficient routing sometimes leads to long delay. How to construct energy-efficient data aggregation trees with QoS properties in different rounds is a complicated problem to be investigated.

Clustering is another approach for saving energy consumption. It selects supreme nodes as cluster-heads, so the high energy dissipation in communicating with the base station is spread to all sensor nodes in the sensor network. The cluster-heads coordinate the transmission in the cluster and aggregate the data from the nodes in their cluster before sending it to a base station. Therefore, the construction of clusters and energy-efficient data aggregation trees in these clusters in different rounds is an extension of my thesis.

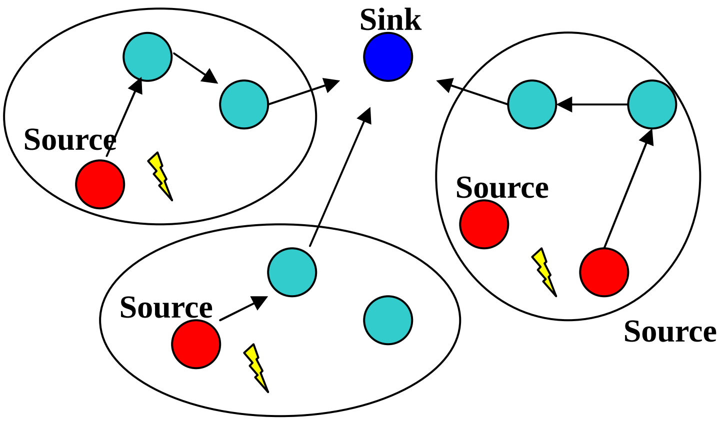


Figure 6-1. An illustrated example of construction of clusters and data aggregation trees in the clusters

In our thesis, the lifetime is defined as the number of rounds until the information about the occurrence of any of events can not be delivered to the sink node. In this definition, we assume that the importance of each event is identical. However, the importance of different events may be different in the reality. By considering this concept, we can set different weight for the events and redefine the system lifetime as the number of rounds until the sum of weight of each event is less than the predefined threshold.

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